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Effects of rapeseed particle size and feed form on growth, nutrient digestibility, and gut physiology in weaned piglets*

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Abstract

Full-fat rapeseed (FFRS) has potential as a sustainable ingredient in monogastric animal nutrition requiring no extensive processing. This study evaluated the effects of grinding and pelleting on the growth performance, nutrient digestibility, and intestinal health of pigs fed diets containing FFRS. Forty-eight castrated male weaned piglets were randomly assigned to six dietary treatments in a 2 × 3 factorial design, varying by feed form (mash or cold-pelleted) and rapeseed particle size (whole, coarse, or fine ground). The experiment lasted 28 days, with FFRS included at 5% during the first 14 days and increased to 10% thereafter. Pelleting significantly improved final body weight, daily weight gain, and feed conversion ratio (FCR) during both the first period (0–14 days) and the entire trial (0–28 days) ($P < 0.001$), whereas grinding had no significant impact on performance outcomes. Apparent ileal digestibility (AID) coefficients of dry matter, valine, and most non-essential amino acids were significantly enhanced by pelleting ($P \leq 0.05$), excluding cysteine and glutamic acid. Pelleting also increased liver weight, ileal digesta pH, ammonia content, and reduced digesta viscosity ($P \leq 0.05$). Grinding alone influenced only the liver weight to body weight gain ratio ($P \leq 0.033$) and caused minor changes in ileal histomorphology. Pelleting significantly increased the concentration of acetic acid in the cecal and colon digesta. In conclusion, pelleting of FFRS-based diets improved growth parameters and nutrient utilization of feed mixtures by weaned piglets, with minimal influence from grinding level in terms of particle size. These findings support the strategic use of raw FFRS in pig diets and highlight the role of physical processing in enhancing its nutritional value.

Key words: rapeseed, piglets, grinding, pelleting, digestibility

Rapeseed is one of the most frequently cultivated oil crops, next to soybean, with annual global production exceeding 87.2 million tons in 2024/2025 (Statista, 2025). Owing to its low glucosinolate and erucic acid profile contents (Chew, 2020), rapeseed has gained significant

attention in both feed and food production. Unprocessed rapeseeds, similar to soybean seeds, are not recommended as a raw material for monogastric animal nutrition due to their high fiber content, which is even greater than that of soybeans (Zaworska-Zakrzewska et al., 2020; Lannuzel et al., 2022). Consequently, in practice rapeseed is routinely subjected to processing, which not only reduces its fiber content, but also produces valuable by-products such as rapeseed oil and protein-rich meal suitable for inclusion in monogastric animal diets (Asl and Niazmand, 2022). In view of the above, numerous studies have been conducted on rapeseed co-products as protein sources in animal nutrition (Kasprzak et al., 2018; Hansen et al., 2020; Zaworska-Zakrzewska et al., 2023). However, the utilization of by-products derived from rapeseed requires further reduction of antinutrient (ANFs) content, which can negatively influence not only their nutritional value, but also growth and health of young animals. The most common processing methods employed to change the chemical composition of by-products include microbial fermentation or enzymatic pre-treatment (Zaworska et al., 2016; Shuai et al., 2023;). Nevertheless, in light of rising energy costs, increasing environmental concerns related to industrial processing, and the need to reduce dependence on imported protein sources, there is a growing interest in re-evaluating the direct use of raw rapeseed in monogastric animal diets (Gołbiewska et al., 2022). This shift aligns with the sustainability objectives outlined in the European Green Deal (52019DC0640 - EN - EUR-Lex - European Union) and the extensive global cultivation of rapeseed. However, realizing this potential requires careful evaluation and the development of strategic innovations to mitigate the limitations associated with its high fiber content and the presence of ANFs, especially in diets intended for young animals.

Pelleting and particle size reduction through grinding are among the most common physical processing methods used to enhance nutrient availability in monogastric diets. These techniques not only improve nutrient digestibility, but also support better feed efficiency, animal performance, and overall profitability in production systems (Lancheros et al., 2020). Pelleting is the most popular treatment in modern pig farming (Fahrenholz, 2012). This hydro-thermal process offers advantages both in terms of animal nutrition and safety of the production process. Feed pelleting improves palatability, minimizes ingredient segregation and feed wastage, and enhances digestibility of dry matter, energy, crude protein, and most amino acids (AAs), thereby improving overall feeding efficiency (Wondra et al., 1995; Lahaye et al., 2008; De Jong et al., 2016; Lancheros et al., 2020). This may result from increased starch gelatinization, altered protein conformation, and inactivation of antinutritional factors, which together improve performance parameters (Wondra et al., 1995; Xing et al., 2004; Svihus and Zimonja, 2011; Ulens et al., 2015; Lewis et al., 2015; Rojas and Stein, 2017).

The efficiency of grinding depends on both particle size and type of feed components (Rojas and Stein, 2015). There are many conflicting studies regarding the impact of particle size on the nutritional efficiency of feed components. Some researchers reported that a reduction of particle size in barley, corn, soybean meal and blue sweet lupin did not affect digestibility of most AAs (Medel et al., 2000; Huang et al., 2015; Rojas and Stein, 2015; Pieper et al., 2016). Other studies, however, showed that reduction in particle size of feedstuffs has a positive effect on digestibility of gross energy and nutrients (Kim et al., 2009; Huang et al., 2015; Rojas and Stein, 2015, 2017). Grinding also affects the performance parameters of pigs either negatively (Ulens et al., 2015) or positively by increasing gain-to-feed ratio, reducing feed intake (Huang et al., 2015; Paulk et al., 2015; Rojas et al., 2016 a), and improving average daily gain (l'Anson et al., 2012). In order to maximize the benefits of grinding, it is necessary to define optimal particle size of feed components.

Given the potential of raw rapeseed as a sustainable source of protein and energy, optimizing physical processing methods such as grinding and pelleting becomes critical for its effective inclusion in pig diets. While considerable research has focused on exploring full-fat

rapeseeds (FFRS) for pig nutrition (Kaczmarek et al., 2020), there is limited insight into how processing variables – such as the degree of grinding and feed form – affect gut morphology and function.

This study introduces a novel experimental approach by simultaneously examining the interplay between mechanical processing of rapeseed and gut health, thereby contributing valuable insights toward optimizing the use of raw FFRS in sustainable monogastric feeding strategies. It was hypothesized that the inclusion of FFRS in diets of weaned pigs, when subjected to varying degrees of grinding and feed pelleting, would positively affect growth performance, enhance nutrient digestibility, and support the functional and morphological development of the digestive tract.

The present study aimed to evaluate the effects of raw full-fat rapeseeds, subjected to different grinding intensities and provided in various feed forms (mash vs cold-pelleted), on growth performance, nutrient digestibility, and selected parameters of intestinal physiology and morphology in growing pigs.

Material and methods

Rapeseeds and feed mixture processing

All feed components used in this experiment were obtained from commercial suppliers. Raw full-fat rapeseeds (*Brassica napus* L.) were processed into three distinct physical forms: (1) whole, unprocessed seeds (WS); (2) coarsely ground (CG) seeds with an average particle size of 1.0 mm; and (3) finely ground (FG) seeds with an average particle size of 0.5 mm. Grinding was performed using a precision disc mill (Skiold A/S, Denmark), ensuring consistent particle size distribution across the respective fractions. Half of prepared feed mixtures were cold-pelleted (without steam) using a BMG granulator (BMG Pelleting Experts, Gdańsk, Poland), with die characteristics: 5.0 mm hole size, 50.0 mm wall thickness, 10 rows, 124 holes per row, 490.0 mm flange diameter, 359.0 mm i.d., 155.0 mm width, and 78.0 mm track width, resulting in pellets with a 5 mm diameter. Table 2 presents the chemical composition of rapeseeds.

Animals, diets, and experimental design

A total of 48 castrated male piglets (Naima × [Pietrain × Duroc]), 6 weeks of age and with an initial body weight (BW) of approximately 12.5 kg were randomly allocated to six dietary treatment groups according to the experimental design presented in Table 1 (n=8 per group). The animals were double housed in straw-bedded boxes for a 28-day trial period. During the first phase of the study (days 1–14), the diets contained 5% full-fat rapeseeds (FFRS), while in the second phase (days 15–28) the inclusion level was increased to 10%. The stepwise inclusion of FFRS in the diets of weaned piglets, from 5% during the initial 14 days to 10% in the subsequent period, was implemented to support digestive adaptation and minimize the risk of adverse effects associated with anti-nutritional factors present in rapeseed, such as glucosinolates and tannins. All feed mixtures were formulated in accordance with the nutrient requirements specified in the Polish feeding standards for pigs (Grela and Skomiał, 2015), as detailed in Table 3. Titanium dioxide (TiO₂) was included in all diets as an indigestible marker to enable the calculation of apparent ileal digestibility (AID) coefficients. The pigs had unrestricted (*ad libitum*) access to both feed and water throughout the experimental period. After the completion of each phase, body weight (BW) was recorded and the daily weight gain (DWG) was calculated. The daily feed intake (DFI) and the feed conversion ratio (FCR) in each phase and throughout the whole experiment were calculated per group.

Sample collection

At the end of the experiment, all pigs from each group were humanely euthanized following electrical stunning, in accordance with ethical and welfare guidelines. Postmortem,

samples of intestinal contents (from the ileum, cecum and colon), the ileal tissue, and the liver were collected into sterile plastic bags and rapidly frozen on dry ice to preserve sample integrity. Fecal samples in the distal rectum were collected from each animal (postmortem), immediately frozen, and subsequently prepared for freeze-drying using a laboratory freeze drier (Epsilon 2-10D LSCplus, Martin Christ Gefriertrocknungsanlagen GmbH, Germany). Prior to freezing, the liver was excised, separated from the surrounding tissue, and weighed using a precision balance (Ohaus Navigator™ NV2202, Ohaus Europe GmbH, Switzerland). The ileal digesta samples were used to determine viscosity, pH, dry matter (DM), crude protein (CP), amino acid (AA) profile, and ammonia concentration. The AID coefficients of nutrients in diets were calculated using the marker method, as described by Adeola (2000). In the cecal digesta, pH and microbial fermentation products – including ammonia, short-chain fatty acids (SCFA), phenol, p-cresol, and indole – were measured, while in the colon digesta pH, sialic acid, and the same microbial metabolites were determined to assess intestinal microbial activity and mucosal health.

Chemical analysis

Representative samples of seeds, diets, and digesta were ground and sieved through a 0.5 mm mesh. Analyses were conducted in duplicate to determine dry matter (DM) and crude protein (CP) according to AOAC (2007) methods 934.01 and 976.05. In addition, seeds were analyzed for ether extract (EE), crude ash, acid detergent fiber, and neutral detergent fiber, assayed with heat-stable amylase and expressed including residual ash) following AOAC (2007) methods 920.39, 942.05, and 973.18, respectively. Amino acid concentrations in seeds, diets and digesta were determined using an AAA-400 Automatic Amino Acid Analyzer (Ingos Ltd., Prague, Czech Republic), with ninhydrin for post-column derivatization. The samples were hydrolyzed with 6 M HCl for 24 h at 110°C (procedure 994.12; AOAC, 2007). The titanium dioxide content was determined according to the method described by Short et al. (1996). The samples were prepared based on the method described by Myers et al. (2004).

The pH of the digesta was measured using a microelectrode and a pH meter (Model 301, Hanna Instruments, Vila do Conde, Portugal). Ammonia content was assayed by the spectrophotometric method using Nessler Reagent (POCH, Gliwice, Poland). To measure viscosity, the digesta samples were centrifuged at 10,000 g for 10 min at 4°C. The supernatant was collected and stored on ice until analysis. Viscosity was measured using a Brookfield Digital DV-II + cone/plate viscometer (Brookfield Engineering Laboratories, Stoughton, MA, USA) maintained at 40°C and at a shear rate of 60 s. Results were expressed in mPa*s ($\text{cP}=0.01 \text{ dyn/s/cm}^2$). Sialic acid content was determined according to the procedure described by Jourdian et al. (1971), and crude mucin was extracted from excreta according to the method described by Lien et al. (1996). Phenol, p-cresol, and indole concentrations were analyzed according to Taciak et al. (2015), using the Shimadzu GC-2010 gas chromatograph (Shimadzu, Kyoto, Japan) equipped with a flame ionization detector (FID), and a Supelco Nukol fused silica capillary column (60 m $\times$ 0.32 mm i.d.; 0.25 μm). Helium was used as a carrier gas. Quantification was performed using standard calibration curves, and results were expressed relative to 5-methylindole as an internal standard. The concentration of SCFAs was determined according to the procedure described by Barszcz et al. (2011), using an HP 5890 Series II gas chromatograph (Hewlett Packard, Waldbronn, Germany) equipped with a flame ionization detector and a Supelco Nukol fused silica capillary column (30 m $\times$ 0.25 mm i.d.; 0.25 μm) (Supelco, Bellefonte, PA, USA), with helium as the carrier gas. Individual SCFA concentrations were calculated using standard curves and in proportion to an internal standard.

The samples of ileum tissues were fixed in 4% formalin buffered with CaCO_3 solution, then washed, dehydrated through a graded ethanol series and xylene, and subsequently embedded in paraffin. Sections of 7 μm in thickness were cut on a rotary microtome (Thermo

Shandon, Runcorn, UK) and then placed on microscope slides coated with a mixture of chicken egg white and glycerine. Specimens were deparaffinized, rehydrated, and then stained with the PAS (periodic acid-Schiff) technique using Schiff reagent for intestinal morphometric analysis. A Delta Optical Evolution 300 microscope integrated with a ToupCamTM camera and MultiScanBase v. 18.03 software (Computer Scanning System II, Warsaw, Poland) was used to measure the height and width of villi, and depth of intestinal crypts (in the replicates). The surface area of villi was calculated from the following equation (Sakamoto et al., 2000): $2\pi \times \frac{WV}{2} \times HV$, (WV – width of villi, HV – height of villi).

Statistical analysis

Data were analyzed as a 2×3 factorial experiment using the general linear model procedures of SAS 9.2 (SAS Institute, NC, USA) with a model including the main effects of grinding and pelleting, as well as their interaction. For all parameters, individual animals served as the experimental unit within each group ($n=8$), except for feed intake, which was analyzed at the pen level ($n=4$). Means were compared with Duncan's range test to determine significant differences among the means at a significance level of $P \leq 0.05$.

Results

There were no mortalities or disease symptoms observed in the animals during the experiment. The growth performance results are shown in Table 4. Grinding had no effect on any of the analyzed performance parameters, whereas pelleting significantly improved ($P \leq 0.05$) the final body weight (FBW, 28 d) by approximately 6%, daily weight gain (DWG) in all the periods by 11–15%, as well as reduced feed conversion ratio (FCR) in the first period (0–14 d) and the entire experiment (0–28 d) by 12–14%. Body weight (BW) after the first period tended to increase in pigs fed pelleted diets. The highest values of DWG and the lowest values of FCR were recorded in pigs fed pelleted diets with coarse-ground rapeseeds (0.569 kg/day and 1.623 kg/day, respectively). The highest DWG in the first period was noted in groups that received pelleted diets with whole and coarse-ground seeds (0.569 and 0.568 kg/day, respectively), while the lowest DWG (0–14 d) was recorded in groups fed mash-form diets with finely ground rapeseeds. DWG over the entire experiment was the highest for pigs fed pelleted diets with coarse-ground seeds, whereas the lowest DWG (0–28 d) was recorded for the group receiving the diet with finely ground rapeseeds in the mash form. The highest FCR, both in the first period (0–14 d) and over the entire experiment (0–28 d), was noted for pigs which received the diet with finely ground rapeseeds in the mash form, while the lowest FCR in days 0–14 was observed in groups fed pelleted diet with finely and coarsely ground rapeseeds. The lowest FCR over the entire experiment was recorded for pigs receiving pelleted feed with coarse-ground rapeseeds. No interactions between the experimental factors were found. Pigs offered pelleted diets with WS or CG presented significantly higher ($P < 0.001$) daily gains during the first 2 weeks in comparison with animals offered mash diets with FG and CG rapeseeds. During the whole experiment the pigs offered CG rapeseeds in the pelleted diet showed better weight gains than those receiving all the mash diets ($P < 0.001$). Simultaneously, the animals offered the other pelleted diets (with WS and FG) gained significantly more weight ($P = 0.007$) than those offered mash feed with FG rapeseeds. FCR of the pelleted diet with FG and CG rapeseeds was significantly better in the first period compared to all the diets in the mash form ($P = 0.011$). Also, the pelleted diet with whole rapeseeds was utilized more efficiently than the mash diet with FG rapeseeds ($P < 0.001$). In the whole experiment, all the pelleted diets were used better than the mash diet with FG rapeseeds, and the pelleted diet with CG rapeseeds was utilized better than the mash diet with the whole seeds ($P < 0.001$).

Grinding of rapeseeds did not significantly ($P>0.05$) affect AID coefficients of crude protein, dry matter, or any amino acids (Table 5), whereas pelleting significantly improved ($P\leq 0.05$) the AID coefficients of DM (by approximately 1%), valine (Val), and all the endogenous amino acids, except for cysteine (Cys) and glutamic acid (Glu). A significant interaction between the experimental factors was observed only for the AID coefficient of threonine (Thr). The AID coefficient of CP was significantly higher for the mash form with CG seeds and the pelleted form with whole and coarse-ground rapeseeds compared to the pelleted feed with finely ground seeds ($P=0.046$). The AID coefficients of Thr and tyrosine (Tyr) were significantly higher ($P\leq 0.05$) in pelleted diets with whole rapeseeds than in the pelleted diets with FG seeds, or mash diets with WS or CG seeds. The AID coefficients of arginine (Arg) and serine (Ser) were significantly higher ($P\leq 0.05$) in pelleted diets with whole rapeseeds than in all the mash feed mixtures. Moreover, the AID coefficient of Ser in pelleted feed was higher than in mash feed with CG seeds. The proline AID coefficient was higher ($P\leq 0.05$) in pelleted feed in the whole seed diet ($P<0.001$), and alanine (ALA) in pelleted feed with WS and CG seeds than in all the mash feeds ($P<0.001$). There was no interaction between the factors.

In Table 6, the effects of experimental factors on physicochemical parameters of the gastrointestinal tract are presented. Grinding increased ($P=0.033$) only the liver weight to body mass ratio, whereas pelleting significantly ($P\leq 0.05$) increased liver weight, ammonia content, and pH value, while simultaneously decreasing viscosity of the ileal digesta. Liver weight was significantly lower in pigs fed the mash diet with WS than those fed pelleted diets with FG and CG rapeseeds. Additionally, pigs receiving the mash diet with CG seeds had lower liver weight than those fed the pelleted diet with FG seeds ($P\leq 0.05$). Ammonia concentration in the ileal digesta of the pigs that consumed the mash diet with CG seeds was significantly lower than in pigs fed pelleted diet with FG and CG seeds, as well as mash diets with WS and FG seeds. Moreover, ammonia concentration in the ileal digesta of the pigs that consumed the pelleted diet with whole seeds was significantly lower than for pelleted diets with CG seeds. Additionally, interactions were only observed between the factors in the case of ammonia content in the ileum and of pH in the cecum. Ileal pH was significantly lower in pigs fed mash diets with CG and FG seeds compared to all the pelleted diets and it was also lower in pigs fed the mash diet with CG seeds than in those receiving the mash diet with whole rapeseeds ($P\leq 0.05$). Also, viscosity of the ileal digesta varied among the diets, with all the pelleted feed mixtures showing significantly lower values ($P<0.001$) compared to mash diets with ground rapeseeds.

Pelleting significantly increased the concentration of acetic acid in the cecal and colon digesta ($P\leq 0.05$) (Table 7). Neither grinding nor pelleting influenced the concentrations of other SCFA in the cecal and colon digesta. No significant interactions between the experimental factors were observed.

Pelleting of the feed and grinding of rapeseeds did not significantly ($P>0.05$) affect the phenol concentration in the cecal digesta (Table 8). However, a significant difference in phenol content in the colon digesta was observed among groups ($P=0.015$). A higher concentration of phenol was noted for groups receiving a pelleted diet with CG rapeseeds and a non-pelleted diet with whole seeds in comparison with the other diets, except for pelleted diets with FG. Also, an interaction between the factors in phenol content was only observed in the colon.

Both experimental factors (pelleting and grinding) did not affect ($P>0.05$) the morphological parameters of the ileum, except for crypt depth (Table 9). Crypt depth was significantly greater ($P=0.030$) in pigs fed the pelleted diet with CG rapeseeds compared to the other pelleted diets and the mash diet with WS. Grinding also had a significant effect on crypt depth ($P=0.008$). There was no interaction between the factors.

Discussion

In our study piglets received 5% and 10% of FFRS in the first and the second period, respectively. These amounts had no negative effects on any performance parameters (BW, DFI, and FCR). The presented results correspond to the findings of Montoya and Leterme (2010), who suggested that up to 10% of FFRS can be implemented without negative effects on the performance of growing pigs. Moreover, other studies (Woyengo et al., 2014) indicated that FFRS addition up to 15% can be used in growing-finishing pig nutrition. Only the FCR was inferior, without a negative effect on other performance parameters (body weight, feed intake, and average daily gain). In our study the grinding process did not affect performance parameters. An older experiment (Busboom et al., 1991) conducted on finishing pigs, in which the authors used different degrees of FFRS grinding (up to 20% in the diet), suggested that grinding reduces FI only, while other performance parameters (daily gain, FCR) remain unchanged. Ulens et al. (2015) suggested that fine grinding (in the nutrition of weanling pigs) negatively affected growth parameters of weaners. There is an abundance of research related to the use of treatments that improve feed utilization. Many authors have suggested that the feed form has a significant impact on the performance of pigs. According to Ulens et al. (2015), pelleted feed has a positive effect on all performance parameters, while O'Meara et al. (2020) observed that pelleting improved the FCR in comparison to the mash form. In contrast, Lewis et al. (2015) stated that nursery pigs fed with pelleted fodder consumed less feed. The current study shows that feed pelleting improves some performance parameters, especially in the first period of the experiment (DWG and FCR), and has no effect on the other parameters (BW and DFI). The improvement in performance parameters during the first period can be attributed to the hydrothermal processing during pelleting, which enhances starch gelatinization, protein denaturation, and partial inactivation of antinutritional factors – all of which improve nutrient digestibility and feed efficiency (Lancheros et al., 2020).

Similarly to our study, Rojas and Stein (2015) and Huang et al. (2015) observed that different grinding feed components (maize) did not affect digestibility of most AAs, energy, and protein in growing and weanling pigs, respectively. The results of Medel et al. (2000) on early weaned pigs showed that grinding of barley had no effect on total tract apparent digestibility of protein and energy. In contrast, Kim et al. (2009) observed that reducing the particle size of lupine seeds increased the AID of most AAs (excluding Pro) in growing pigs. Skiba et al. (2002) demonstrated that fine grinding of FFRS resulted in an increase in energy digestibility in growing pigs. Rojas and Stein (2017), according to other research, suggested that the digestibility of nutrients depends on specific ingredients. Lahaye et al. (2008) and Rojas et al. (2016 b) observed that pelleting of the feed mixture increased digestibility of most AAs, CP, and DM in the nutrition of growing pigs. Skiba et al. (2002) showed that pelleting of feed with FFRS increases energy and nutrient digestibility, but grinding of rapeseeds had an influence in the case of mash diets only. In our study the pelleting process had a positive effect on AID coefficients of DM, Val, and most endogenous AAs. In experiments with FFRS in broiler chicken nutrition conducted by Kaczmarek et al. (2020), both feed pelleting and seed grinding increased digestibility of crude protein.

Other studies concerning the influence of the feed form and grinding of components on liver weight have shown that neither of these factors has an effect on this parameter (Liermann et al., 2015). In contrast, our study shows that pelleting associated with grinding affects liver weight. Significantly ($P < 0.05$) higher liver weight was recorded in pigs fed the pelleted form in comparison with the mash form. The increase in liver weight in pigs fed pelleted diets compared to mash diets may indicate physiological and metabolic adaptive processes related to nutrient processing and overall metabolic activity (Karimirad et al., 2020). This is attributable to the fact that pelleted feed typically exhibits enhanced digestibility and nutrient

bioavailability, which may result in a greater influx of nutrients (amino acids, fatty acids, glucose) to the liver via the portal vein and stimulate increased activity of metabolic pathways such as gluconeogenesis, lipogenesis, transamination, and detoxification (Kiarie and Mills, 2019). As a side effect, this may lead to physiological (non-pathological) liver hypertrophy in response to a greater metabolic load. This observation is supported by our findings, as the liver-to-body weight ratio remained unchanged, suggesting an adaptive, rather than pathological, response.

The elevated ammonia concentration and pH values in the ileum of pigs fed pelleted diets, particularly those with fine and coarse-ground rapeseeds, point toward an increased microbial deamination of undigested proteins or amino acids in the distal small intestine. These alterations may stem from faster digesta transit or greater protein availability, typical for pelleted feed (Canibe et al., 2005). Interestingly, pigs receiving mash diets with coarsely ground seeds exhibited the lowest ammonia levels, indicating a slower fermentation profile and possibly more balanced protein utilization. The observed interactions between grinding and pelleting on ileal ammonia and cecal pH highlight the complexity of nutrient–microbiota interactions and underline the need to consider feed mixture structure and its thermal treatment jointly. In turn, the observed interaction between feed pelleting and grinding in our study affects intestinal ammonia concentration in pigs primarily through modifications in protein digestion dynamics and microbial fermentation patterns in the gut. Pelleting increases starch gelatinization and improves nutrient homogeneity, enhancing dry matter and protein digestibility in the upper gastrointestinal tract. Additionally, pelleting lowered digesta viscosity, facilitating better enzyme–substrate interaction and absorption of protein and some amino acids in the small intestine (Carré et al., 2002). Coarse particle size may slow gastric emptying and promote more extensive enzymatic digestion, while fine grinding increases surface area, but may lead to faster gut transit or excessive fermentation if poorly digested proteins escape absorption. When pelleted diets are combined with coarser particle sizes, a synergistic effect can occur: pelleting improves digestibility, while coarser particles reduce fermentation substrate availability in the intestine. Such changes in digesta rheology may enhance nutrient absorption, but may also shift the microbial composition toward less fermentative profiles.

Only the concentration of acetic acid was significantly increased in the cecal and colon digesta of pigs fed pelleted diets, with no effect on other SCFAs. This suggests that pelleting selectively influences bacterial populations or substrate availability favoring acetate-producing species (Louis and Flint, 2017). The phenol content was not broadly affected by the processing methods; however, higher levels were observed in pigs receiving either pelleted diets with coarse-ground seeds or mash diets with whole seeds, which may be related to differing rates of protein degradation and microbial phenolic production (Jha and Berrocso, 2016).

There are several experiments associated with the feed form, grinding of seeds, and their impact on the histomorphometrics of the small intestine. Morel and Cottam (2007) found no effect of degree of grinding on the size of the villi and the depth of the crypts. Other studies (Hedemann et al., 2005) showed that coarse grinding of components has an impact on the height of the villus and intestinal villus surface area only in combination with feed pelleting. Our study shows that grinding has an impact on crypt depth. Coarsely ground rapeseeds have the greatest crypt depth, both in the case of mash and pelleted forms. Deeper crypts may indicate enhanced cellular turnover and mucosal renewal, potentially as an adaptive response to increased absorptive demands (Pluske et al., 1996). Grinding alone also significantly affected crypt depth, further supporting the relevance of feed particle size in shaping gut morphology. The greater crypt depth measured in the ileum of pigs fed coarsely ground rapeseeds in the pelleted form, as compared to the mash form may be explained by greater absorption in this intestinal segment.

Conclusion

In conclusion, raw rapeseed products have an important nutritional impact by improving performance results. The efficacy depends mainly on the pelleting process. This study demonstrates that pelletized, coarsely ground, and whole rapeseeds had a positive effect on daily weight gain and feed conversion ratio, especially after the first period of piglet feeding. Digestibility of DM, CP, and AAs depends on the processing method of the diets. Grinding of FFRS had no effect on this parameter, but pelleting did improve digestibility of most ingredients. Pelleting also significantly decreased viscosity in the ileal digesta. Histomorphometric (crypt depth) parameters could also be improved in pigs receiving a pelleted diet with coarse-ground FFRS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical approval

The experimental procedures complied with the guidelines of the Local Ethical Committee for Experiments on Animals in Poznań regarding animal experimentation and animal care under study (EU Directive 2010/63/EU for animal experiments). The experiment was approved by the Local Ethical Committee in Poznań – Resolution No. 43/2011 of 15 May 2011. All samples (biological material) of liver, tissue, and digesta were collected after slaughter.

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Table 1. The experimental treatments

	Treatment					
Processing	1	2	3	4	5	6
Grinding	WS	FG	CG	WS	FG	CG
Pelleting	-	-	-	+	+	+

“-“ – no treatment; “+” – treatment; WS – whole seeds; FG – finely ground (0.5 mm diameter); CG – coarsely ground (1.0 mm diameter).

Table 2. Chemical composition of rapeseed used in the experiments (% in feed) (n=2)

	Content
Dry matter	90.01
Crude protein	20.05
Ether extract	43.70
Crude ash	3.88
Acid detergent fiber	18.81
Neutral detergent fiber	28.80
Essential amino acids	
Threonine	0.9
Valine	1.01
Methionine	0.4
Isoleucine	1.42
Leucine	1.44
Phenylalanine	0.8
Lysine	1.2
Histidine	0.6
Non-essential amino acids	
Tyrosine	0.6
Arginine	1.21
Aspartic acid	1.39
Cysteine	0.5
Proline	1.18
Serine	0.7
Glutamic acid	3.30
Alanine	0.9

Table 3. Composition and nutritional value of experimental diets (%)

Components (% w/w)	Day 1–14	Day 15–28
Soybean meal	17.00	15.50
Full-fat rapeseeds ¹	5.00	10.00
Triticale	30.00	30.00
Wheat	44.04	40.53
Premix 0.5% ²	0.500	0.500
Limestone	0.900	0.900
Phosphate 1-Ca	1.10	1.10
NaCl	0.330	0.340
L-Lysine HCl	0.450	0.450
DL-Methionine	0.130	0.130
DL-Threonine	0.250	0.250
TiO ₂	0.300	0.300
Calculated nutritional value in dry matter		
Metabolizable energy (MJ/kg)	13.70	14.08
Crude protein (%)	18.10	18.00
Digestible protein (%)	15.10	15.00
Digestible lysine (%)	1.14	1.14
Digestible methionine (%)	0.370	0.370
Digestible tryptophan (%)	0.705	0.704
Digestible threonine (%)	0.245	0.245
Ca (%)	0.783	0.787
P (%)	0.656	0.665
Digestible P (%)	0.425	0.426
Na (%)	0.150	0.150

¹The experimental diets differed in the physical form of feed (meal vs pelleted) and rapeseed particle size (whole seeds, coarsely ground, finely ground).

²Premix—mineral and vitamin premix content (per 1 kg): choline chloride – 40,000 mg, Fe – 15,000 mg, Cu – 4000 mg, Co – 60 mg, Mn – 6000 mg, Zn – 15,000 mg, I – 120 mg, Se – 30 mg, antioxidants (butylated hydroxyanisole, butylated hydroxytoluene); vitamin A – 1,500,000 IU, vitamin D₃ – 300,000 IU; vitamin E – 10,500 mg, vitamin K₃ – 220 mg, vitamin B₁ – 220 mg, vitamin B₂ – 600 mg, vitamin B₆ – 450 mg, pantothenic acid – 1500 mg, nicotinic acid – 3000 mg, folic acid – 300 mg, vitamin B₁₂ – 3700 µg, biotin – 15,000 µg, Ca – 260 g.

Table 4. Performance results of piglets (n=8)

Grinding	WS	FG	CG	WS	FG	CG	P-value	P-value		Interaction
Pelleting	-	-	-	+	+	+		grinding	pelleting	
IBW 0 d (kg)	12.74	12.59	12.69	12.53	12.50	12.44	0.995	0.974	0.579	0.978
BW 14 d (kg)	19.61	19.28	19.51	20.45	20.21	20.40	0.524	0.863	0.054	0.996
FBW 28 d (kg)	28.71	27.86	28.99	30.26	29.94	30.95	0.157	0.476	0.012	0.951
DWG (kg/day)										
0–14 d	0.491 ab	0.476 b	0.486 b	0.568 a	0.551 ab	0.569 a	0.027	0.803	<0.001	0.988
15–28 d	0.650	0.613	0.678	0.701	0.695	0.753	0.209	0.291	0.034	0.916
0–28 d	0.571 bc	0.546 c	0.583 bc	0.635 ab	0.624 ab	0.661 a	0.007	0.276	<0.001	0.935
DFI (kg)										
0–14 d	0.879	0.861	0.856	0.881	0.838	0.866	0.832	0.466	0.854	0.775
15–28 d	1.20	1.25	1.23	1.22	1.23	1.28	0.870	0.569	0.663	0.786
0–28 d	1.04	1.06	1.04	1.05	1.04	1.07	0.959	0.883	0.769	0.711
FCR (kg/kg)										
0–14 d	1.80 ab	1.82 a	1.78 ab	1.59 bc	1.53 c	1.65 c	0.011	0.923	<0.001	0.845
15–28 d	1.86	2.04	1.82	1.78	1.86	1.72	0.261	0.158	0.119	0.828
0–28 d	1.83 ab	1.94 a	1.80 abc	1.68 bc	1.68 bc	1.62 c	0.007	0.278	<0.001	0.667

The results are reported as mean values; '-' – no treatment; '+' – treatment; WS – whole seeds; FG – finely ground (0.5 mm diameter); CG – coarsely ground (1.0 mm diameter); IBW – initial body weight; BW – body weight (14th day); FBW – final body weight (28th day); DWG – daily weight gains; DFI – daily feed intake; FCR – feed conversion ratio; a, b, c – means with different letters within a row are significantly different at $P \leq 0.05$.

Table 5. Apparent ileal digestibility coefficients (%) of crude protein, dry matter, and amino acids in the diets (n=8)

Grinding	WS	FG	CG	WS	FG	CG	P-value	P-value		Interaction
Pelleting	-	-	-	+	+	+		grinding	pelleting	
Dry matter	95.97	96.05	95.55	97.36	96.53	96.92	0.061	0.582	0.004	0.503
Crude protein	57.21 ab	60.27 ab	63.92 a	68.18 a	50.89 b	64.32 a	0.046	0.054	0.716	0.056
Essential amino acids										
threonine	62.39 b	66.55 ab	62.89 b	72.33 a	63.05 b	68.02 ab	0.042	0.350	0.054	0.042
valine	60.33	64.28	62.23	69.15	61.98	70.03	0.073	0.574	0.042	0.105
methionine	76.96	78.72	80.95	83.42	76.06	81.35	0.116	0.225	0.432	0.107
isoleucine	63.87	66.18	65.69	71.31	66.06	70.65	0.202	0.710	0.053	0.315
leucine	66.82	70.88	69.44	74.01	68.85	73.15	0.231	0.834	0.132	0.154
phenylalanine	71.09	73.83	71.94	77.02	72.91	75.92	0.375	0.951	0.118	0.319
lysine	67.56	74.12	72.61	75.49	71.75	74.19	0.195	0.674	0.208	0.082
histidine	63.29	66.14	66.15	68.47	62.00	69.62	0.436	0.477	0.548	0.281
Non-essential amino acids										
tyrosine	65.81 b	69.24 ab	67.67 b	75.81 a	68.19 b	72.36 ab	0.048	0.485	0.020	0.088
arginine	74.48 b	76.95 b	76.12 b	83.65 a	79.24 ab	79.29 ab	0.033	0.584	0.004	0.188
aspartic acid	57.75	59.02	59.74	66.82	62.31	61.99	0.137	0.781	0.027	0.347
cysteine	60.11	58.34	60.67	67.85	59.91	64.12	0.564	0.514	0.225	0.747
proline	66.88 b	64.45 b	71.22 b	81.42 a	82.17 a	80.73 a	<0.001	0.918	<0.001	0.469
serine	62.34 bc	63.52 bc	60.22 c	73.79 a	67.53 abc	69.65 ab	0.002	0.215	<0.001	0.286
glutamic acid	74.98	76.30	78.10	81.32	73.91	78.81	0.294	0.379	0.465	0.233
alanine	41.42 b	44.99 b	47.06 b	58.61 a	50.87 ab	57.92 a	0.006	0.516	<0.001	0.283

The results are reported as mean values; '-' – no treatment; '+' – treatment; WS – whole seeds; FG – finely ground (0.5 mm diameter); CG – coarsely ground (1.0 mm diameter); a, b, c – means with different letters within a row are significantly different at $P \leq 0.05$.

Table 6. Physical parameters of the liver, sialic acid and ammonia concentration, digesta pH and viscosity in the colon, ileum, and cecum (n=8)

Grinding	WS	FG	CG	WS	FG	CG	P-value	P-value		Interaction
Pelleting	-	-	-	+	+	+		grinding	pelleting	
Liver weight (g)	952.34 c	1011.9 abc	989.32 bc	1050.0 abc	1131.0 a	1106.2 ab	0.026	0.225	0.002	0.959
Liver/BM ratio (kg/kg)	0.033	0.036	0.034	0.035	0.038	0.036	0.093	0.033	0.105	0.999
Sialic acid (mg/L)										
colon	837.70	941.90	981.10	1092.1	1075.6	875.00	0.612	0.803	0.353	0.343
Ammonia (mmol/L)										
ileum	6.63 bc	8.63 ab	5.90 c	9.48 a	8.37 ab	8.94 a	0.008	0.411	0.003	0.045
cecum	10.60	8.26	7.58	9.86	8.67	9.60	0.469	0.235	0.550	0.492
pH										
ileum	5.91 ab	5.55 bc	5.06 c	6.32 a	6.29 a	6.33 a	<0.001	0.123	<0.001	0.070
cecum	6.38	6.07	5.95	5.94	5.80	6.28	0.077	0.291	0.356	0.033
colon	6.19	6.19	6.23	6.41	6.37	6.34	0.753	0.991	0.125	0.927
Viscosity (cP)										
ileum	2.08 ab	2.54 a	2.57 a	1.67 b	1.59 b	1.53 b	0.002	0.664	<0.001	0.289

The results are reported as mean values; '-' – no treatment; '+' – treatment; WS – whole seeds; FG – finely ground (0.5 mm diameter); CG – coarsely ground (1.0 mm diameter); BM – body mass; a, b, c – means with different letters within a row are significantly different at $P \leq 0.05$.

Table 7. Concentrations of short-chain fatty acids ($\mu\text{mol/g}$ digesta) in the pigs' cecal and colon digesta (n=8)

Table 7. Concentrations of short-chain fatty acids (μmol/g digesta) in the pigs										
Grinding	WS	FG	CG	WS	FG	CG	P-value	P-value		Interaction
Pelleting	-	-	-	+	+	+		grinding	pelleting	
Cecal										
Acetic acid	37.44	37.812	43.58	46.74	48.21	42.25	0.143	0.957	0.033	0.158
Propionic acid	19.38	19.36	23.68	22.70	22.59	22.01	0.173	0.587	0.116	0.118
Isobutyric acid	0.510	0.462	0.529	0.614	0.631	0.520	0.233	0.772	0.058	0.252
Butyric acid	10.84	10.23	13.81	12.88	15.41	12.84	0.308	0.689	0.151	0.203
Isovaleric acid	0.260	0.215	0.309	0.380	0.374	0.285	0.343	0.894	0.094	0.274
Valeric acid	3.40	2.87	4.11	3.31	4.05	3.10	0.490	0.919	0.992	0.127
Colon										
Acetic acid	53.49	56.76	51.94	51.48	46.96	47.04	0.271	0.633	0.045	0.495
Propionic acid	23.68	27.03	26.52	23.02	22.73	22.01	0.570	0.811	0.111	0.662
Isobutyric acid	1.39	1.52	1.32	1.45	1.11	1.16	0.409	0.529	0.202	0.340
Butyric acid	14.03	14.36	15.71	14.26	15.37	13.92	0.934	0.862	0.879	0.622
Isovaleric acid	1.39	1.55	1.35	1.57	1.135	1.12	0.630	0.584	0.423	0.428
Valeric acid	4.54	4.578	5.09	4.45	5.07	4.19	0.808	0.825	0.698	0.428

The results are reported as mean values; '-' – no treatment; '+' – treatment; WS – whole seeds; FG – finely ground (0.5 mm diameter); CG – coarsely ground (1.0 mm diameter).

Table 8. Phenol, p-cresol, and indole contents in the digesta of cecum and colon ($\mu\text{M} \cdot 10^{-2}/\text{g}$ of digesta) (n=8)

Table 8. Phenol, p-Cresol, and indole contents in the digesta of cecum and colon ($\mu\text{M} \cdot 10^{-3} / \text{g}$ of digesta) (n=8)										
Grinding	WS	FG	CG	WS	FG	CG	P-value	P-value		Interaction
Pelleting	-	-	-	+	+	+		grinding	pelleting	
Phenol										
cecum	0.473	0.463	0.490	0.514	0.505	0.483	0.476	0.898	0.131	0.376
colon	0.478 a	0.429 b	0.424 b	0.423 b	0.452 ab	0.473 a	0.015	0.799	0.527	0.001
p-Cresol										
cecum	4.20	4.56	3.95	4.39	4.09	4.02	0.366	0.246	0.710	0.301
colon	10.31	12.95	10.70	12.31	11.43	10.55	0.559	0.419	0.909	0.342
Indole										
cecum	6.19	6.51	6.90	6.54	6.39	6.41	0.180	0.279	0.559	0.089
colon	6.45	7.01	6.86	6.85	6.63	6.86	0.309	0.457	0.971	0.103

The results are reported as mean values; '-' – no treatment; '+' – treatment; WS – whole seeds; FG – finely ground (0.5 mm diameter); CG – coarsely ground (1.0 mm diameter); a, b – means with different letters within a row are significantly different at $P \leq 0.05$.

Table 9. Morphometric indices of the ileum (n=8)

Grinding	WS	FG	CG	WS	FG	CG	P-value	P-value		Interaction
Pelleting	-	-	-	+	+	+		grinding	pelleting	
Villus length (μm)	348.16	358.76	390.16	376.49	365.03	348.16	0.743	0.927	0.904	0.291
Villus width (μm)	132.92	144.27	134.72	139.04	138.29	141.26	0.896	0.763	0.708	0.616
Crypt depth (μm)	93.75 b	103.50 ab	110.38 ab	101.45 b	97.57 b	120.73 a	0.030	0.008	0.408	0.326
Surface area (μm^2)	1471.4	1647.5	1687.3	1658.5	1610.1	1583.4	0.939	0.878	0.902	0.608

The results are reported as mean values; '-' – no treatment; '+' – treatment; WS – whole seeds; FG – finely ground (0.5 mm diameter); CG – coarsely ground (1.0 mm diameter); a, b – means with different letters within a row are significantly different at $P \leq 0.05$.