ARCHIVES OF ANIMAL NUTRITION
2024, VOL. 78, NO. 2, 142–158
https://doi.org/10.1080/1745039X.2024.2368284

Taylor & Francis
Taylor & Francis Group

Performance and nutrient digestibility of growing pigs fed highly or low fermentable coarse or finely ground fibre-rich feedstuffs

Eva-Maria Saliu[a], Johannes Schulze Holthausen[a], Volker Wilke[b] and Jürgen Zentek[a]

[a]Institute of Animal Nutrition, Freie Universität Berlin, Berlin, Germany; [b]Institute for Animal Nutrition, University of Veterinary Medicine Hannover, Hanover, Germany

ABSTRACT
Dietary fibre is mainly classified according to its chemical characteristics but structure and particle size of fibre-rich feedstuff can also be decisive for digestion and performance. So far, only few studies investigated this in pigs. This experiment aimed to compare coarse and finely ground dried hemp plants and apple pomace regarding performance and ileal and total tract nutrient digestibility of growing pigs. Coarse or finely ground apple pomace or dried hemp plants were added to the diet of 56 nine weeks old growing pigs (DanBred x Duroc), housed in flat decks with each 2 animals. The growing pigs received the experimental diets for three weeks while performance was recorded. Eight pigs per group were sacrificed and digesta and organ tissue sampled. The stomach health was evaluated by visually scoring of the mucosa integrity. Apparent ileal (AID) and total tract digestibility (ATTD) were calculated using titanium dioxide as marker. Statistical analyses were performed using two-way ANOVA ($p < 0.05$). The highest feed intake (fibre particle size, $p = 0.018$) and bodyweight gain (fibre particle size, $p = 0.018$; fibre source x particle size interaction, $p = 0.040$), was observed in animals fed finely ground apple pomace, while the feed conversion ratio was 8–12% lower in pigs fed finely ground fibre sources ($p = 0.012$). No differences in stomach mucosa integrity were detected between the groups. The relative pancreas ($p = 0.045$), stomach ($p < 0.001$), and jejunum ($p = 0.010$) weights were higher in animals fed diets containing apple pomace. In contrast, the relative liver, caecum and colon weights were not affected by fibre source or particle size. The AID of protein and amino acids was not affected, while ATTD was increased by fibre source (hemp vs. apple pomace) reducing faecal nitrogen excretion. The AID of calcium was increased when diets contained apple pomace ($p < 0.001$), while zinc AID and ATTD were enhanced when diets contained dried hemp ($p = 0.016$; $p = 0.016$, respectively). Our results suggest that the structure as well as the chemical characteristics should be considered in a future fibre evaluation system in pigs.

ARTICLE HISTORY
Received 2 April 2024
Accepted 11 June 2024

KEYWORDS
Apple pomace; byproducts; dietary fibre; digestive system; hemp; piglets; stomach ulcer; viscosity

CONTACT Eva-Maria Saliu ✉ Eva-Maria.Saliu@fu-berlin.de

1. Background

For decades, pork production relied on nutrient and energy dense diets, to provide rapid bodyweight gain (BWG) and favourable feed conversion ratio (FCR). The efforts to reduce FCR promises high productivity at lower feed costs (Edwards et al. 1989). Highly concentrated diets are used to achieve these goals, and dietary fibre is often kept at low concentrations, as it dilutes the nutrient and energy density and reduces nutrient digestibility in the diet (Röhe and Zentek 2021; Grześkowiak et al. 2023). However, more and more beneficial aspects were reported of feeding diets containing more dietary fibres, which indicates a new and more differentiated perception of dietary fibre in swine nutrition (Grześkowiak et al. 2023). Another aspect, which has to be considered, is the fact that the exponentially growing world population and the limited arable land calls for feed, which does not directly compete with food for human consumption (Muscat et al. 2020). While common ingredients in concentrates, as currently used in pig feed, often contain components which also could be consumed by humans, fibre-rich by-products from food production are promising alternatives. Besides these aspects, there are further benefits from fibre-rich diets for the animals. Hence, fibre-rich feedstuff is commonly offered to pigs and can influence the gut morphology, immune system and the intestinal microbial community and may enhance animal wellbeing and health (Grześkowiak et al. 2023). However, the main concern of fibre-rich diets is the reduction in performance. This can often be explained by unbalanced diets where fibre-rich feedstuff is added to a diet rather than integrated to the formulation at an isocaloric and isonitrogenous approach (Röhe and Zentek 2021). Another important aspect is its impact on digestibility of other nutrients, e.g. through affecting characteristics of the digesta (Wilke et al. 2021), but this aspect has not been investigated systematically considering physical and chemical characteristics of dietary fibre. Instead, dietary fibre is commonly evaluated based solely on its chemical composition, often characterised as soluble/insoluble or fermentable/non-fermentable dietary fibre. Nevertheless, it is well known from ruminants that the structure of fibre-rich feedstuff also is of importance (Mertens 1997; Zebeli et al. 2012). In pigs, this has only been studied scarcely, but published data indicated that fibre particle size can be decisive (Molist et al. 2012, 2014).

Apple (*Malus domestica* Borkh.) is cultivated worldwide (Musacchi and Serra 2018) and approximately 16–19% of the harvested apples are processed to apple juice (Lyu et al. 2020). Apple pomace is the solid by-product from apple juice production. It is a valuable feed ingredient with relatively low amounts of protein (1.2–5.8% DM) and fat (0.6–4.2% DM), but high concentrations of carbohydrates (<84% DM) with a considerably high fibre proportion (Total Dietary Fibre (TDF): 14.5–42.5% DM) (Vendruscolo et al. 2008; Lyu et al. 2020). Apple pomace is specifically of interest, as it contains a high concentration of pectin (<8% DM), but this varies depending on the production process and can be largely pectin-free or contain a residual amount of pectin. Some beneficial effects of feeding apple pomace on performance were previously reported. Hence, feeding weaned piglets (8–23 kg bodyweight (BW)) or growing pigs (25–107 kg BW) diets with 4 or 8–10% apple pomace, respectively, reduced the feed conversion ratio (FCR; 1.79 vs. 1.59

and 3.04 vs. 2.84) compared to a control group without pomace added to the diet (Pieszka et al. 2017; Dufourny et al. 2021).

Hemp (*Cannabis sativa* L.) belongs to the *Cannabaceae* family (Small and Cronquist 1976) and is widely known for its psychoactive properties and pharmacological use. Industrial hemp, with low concentrations of psychoactive components (tetrahydrocannabinol acid (THC) < 0.2–0.3%), is traditionally used as feed. It is especially of interest, as it is a sustainable crop alternative with multi-functional use (Tedeschi et al. 2022). Hemp, and especially the seeds, are of interest in human and animal nutrition due to its high protein (20–28%) and polyunsaturated fatty acid content (27–31%), which have a favourable n6/n3 ratio of 2.5–3.5:1 (Vonapartis et al. 2015; Faugno et al. 2019). Leaves, stems and seeds are also of interest due to the dietary fibre content. Hemp seeds and oil can be fed directly or the by-products from hemp oil production can be used as valuable protein sources in animal nutrition (Crini et al. 2020). Furthermore, protein extracts might be used or the entire plant can be offered as feedstuff. While several studies were conducted in poultry and ruminants, hemp as a feedstuff for pigs was only investigated scarcely (Della Rocca and Di Salvo 2020).

It was hypothesised that both chemical and physical characteristics of fibre-rich feed components influence nutrient digestibility and performance in pigs. As expansion of the stomach increases satiety, we hypothesised that larger particle sizes may increase satiety further and thus, decrease feed intake. Given that high feed intake is linked to performance, this could potentially have a negative effect on BWG.

Especially soluble dietary fibres can increase the production of SCFA in the hindgut and thereby contribute to energy supply and increase performance (Krogh et al. 2015). An increase in SCFA was also observed when dietary fibre was offered at larger particle size (Molist et al. 2012). We therefore hypothesised that soluble fibre sources at large particle size increase growth performance.

Soluble fibres can increase viscosity of the digesta and thereby reduce digestibility of energy and nutrients (Bach Knudsen et al. 1991). Insoluble fibres may stimulate the production of the pancreatic enzymes and increase digestibility. Smaller particle size in the diet increases the surface for enzymatic reaction and thus we hypothesised that diets containing finely ground hemp may show the highest ileal digestibility of nutrients and energy.

Thus, the study aimed to evaluate the impact of fibre type (apple pomace vs. dried hemp) and fibre particle size (coarse vs. finely ground) on performance, nutrient digestibility, pH of intestinal content and stomach mucosa integrity.

2. Material and methods

2.1. Study design, animals and husbandry

During a three-week time period, growing pigs were fed balanced, isocaloric and isonitrogenous experimental diets containing either a low or a highly fermentable fibre-rich feedstuff, which was either coarse or finely ground. The diets were formulated to meet or exceed the recommendations for growing pigs provided by the Society of Nutrition Physiology (GfE, 2006) and contained titanium dioxide (TiO_2) as indigestible marker (Table 1). Effects of the fibre sources and their particle size were compared in a two-by-two factorial design. Thus, 56 nine weeks old growing pigs (31 males and 25 females; DanBred × Duroc, 21.8 ± 4.1 kg BW) were randomly allocated to four different feeding groups, with seven replicates (pens) per feeding group each and 2 pigs per pen (Table 1). The pigs were distributed to 28 flat deck pens according to their BW and sex. The barn temperature was successively reduced from 29°C to 20°C, and light was provided for 12 h per day (6:00 until 18:00). The pigs had *ad libitum* access to drinking water and feed, the latter was offered dry as meal.

The animal trial was approved by the Regional Office for Health and Social Affairs Berlin (LAGeSo, StN 023/21). All pigs used in the study were kept and treated according to European Union Directive 2010/63/EU on the protection of animals used for scientific purposes, considering the alignments made by the regulation (EU) 2019/1010. Additionally, the recommendation of Commission 2007/526/CE covering guidelines for the accommodation and care of animals used for experimental and other scientific purpose were followed.

2.2. Grinding of the fibre source

The upper 20 cm of hemp plants were harvested and subjected to hot-air drying and chopped in a straw mill with a 20 mm mesh width (Strohmühle KSTAS, Voran Maschinen GmbH, Austria) to be fed as the coarse hemp option. To obtain the fine particle size, the coarse chopped hemp was milled a second time in the straw mill, but with a 10 mm mesh width and then ground in an electric kitchen blender (Bosch MUM 4; Robert Bosch Hausgeräte GmbH, Germany). The dried apple pomace was either fed intact (coarse particle size) or ground with an electric mill for cereals using a mesh width of 0.8 mm (Elettromulino Magico EMC60, ama S.p.A. accessori macchine Agricole, Italy).

2.3. Performance and sampling

Feed intake (FI) per pen and individual BW were recorded weekly to calculate total BWG, average daily gain (ADG), average daily feed intake (ADFI) and feed conversion ratio (FCR = FI/BWG), where the pens were considered as experimental unit. To consider minor differences in energy content between diets, the energy intake (EI) and energy conversion ratio (ECR = EI/BWG) were calculated as well. The faecal consistency and health status were recorded daily. The faecal consistence was evaluated on pen-basis using a scale from 1 to 5, starting at liquid diarrhoea (1) and reaching up to hard faecal pellets (5). Score 3 was considered physiological. At the end of the feeding period, eight growing pigs per group were sacrificed by intracardial injection with 3 ml/animal T61 (Hoechst Veterinär, Germany), a mixture of tetracaine hydrochloride (5 mg/ml), mebezoniumiodide (50 mg/ml) and embutramide (200 mg/ml). The euthanasia was preceded by an intramuscular anaesthesia consisting of 20 mg ketamine-hydrochloride/kg BW (100 mg/ml; Ultrospec™, Serumwerk Bernburg AG, Germany) and 2 mg azaperon/kg BW (40 mg/ml; Ultrospec™, Elanco GmbH, Germany). The stomach, jejunum, ileum, caecum and colon were weighted full and empty and the weights of liver and the pancreas were recorded and the jejunum length measured. Next

Table 1. Ingredients and composition of experimental diets and fibre-rich feedstuff.

Feed type	Complete diets				Raw materials	
Fibre type	Dried hemp		Apple pomace			
Fibre particle size	Fine	Coarse	Fine	Coarse	Dried hemp	Apple pomace[a]
Ingredients [g/kg]						
Soybean meal	194.7	194.7	238.3	238.3		
Corn	578	578	525.3	525.3		
Dried hemp	140	140	0	0		
Apple pomace	0	0	155	155		
Oil	35.5	35.5	31.7	31.7		
Mineral supplement	20	20	20	20		
Calciumcarbonate	18	18	18	18		
Titanium dioxide	3	3	3	3		
L-lysine	4.9	4.9	4	4		
D-/L-methionine	2.4	2.4	2	2		
Threonine	2.6	2.6	2.1	2.1		
Tryptophane	0.9	0.9	0.6	0.6		
Analysed nutrient content						
[b]ME [MJ/kg feed]	13.6	13.8	13.2	13.2		
DM [g/kg feed]	901	903	911	908	914	915
Crude ash [g/kg DM]	61.2	61.7	52.2	49.8	98.3	14.0
Crude protein [g/kg DM]	190	185	185	181	163	50.6
Ether extract [g/kg DM]	79.7	84.7	61.7	59.5	35.1	17.7
Crude fibre [g/kg DM]	60.2	58.1	70.2	67.4	223	183
Starch [g/kg DM]	458	469	446	443		
NDF [g/kg DM]	171	171	227	210	350	335
ADF [g/kg DM]	74.0	78.4	91.3	97.3	277	263
ADL [g/kg DM]	32.8	29.2	28.7	33.7	48.7	128.7
TDF [g/kg DM]	166	165	215	237	461	459
i-DF [g/kg DM]	163	157	187	205	428	349
s-DF [g/kg DM]	3.36	8.55	27.57	31.61	32.7	110
TiO2 [g/kg DM]	3.24	3.22	3.47	3.16		
P [g/kg DM]	3.74	3.74	5.49	3.22		
Ca [g/kg DM]	12.7	12.7	6.9	8.9		
Cu [mg/kg DM]	36.8	29.7	32.1	29.4		
Zn [mg/kg DM]	168	142	190	158		
Indispensable amino acids [g/kg DM]						
Arginine	12.1	11.0	11.9	11.7		
Histidine	5.1	4.6	5.0	5.0		
Isoleucine	8.3	7.4	8.4	8.3		
Leucine	16.9	15	16.4	16.3		
Lysine	13.7	12.5	13.1	13.2		
Methionine	4.7	4.3	4.3	3.9		
Phenylanaline	10.0	9.0	10.0	9.9		
Threonine	9.3	8.3	8.9	8.6		
Valine	14.5	13.9	9.1	15.2		
Dispensable amino acids [g/kg DM]						
Alanine	10.2	9.2	9.9	9.8		
Aspartic acid	6.1	5.4	6.1	6.0		
Cystine	3.3	3.0	3.0	3.0		
Glutamic acid	35.1	31.2	34.9	34.7		
Glycine	8.1	7.4	8.2	8.1		
Proline	10.9	9.8	10.5	10.5		
Serine	9.4	8.4	9.4	9.3		
Tyrosine	5.8	5.4	5.8	5.8		
Particle size [g/kg]						
>4.0 mm	4	4	0	40		
3.9–2.5	2	8	2	72		
2.4–1.0	226	294	251	313		
0.99–0.63	218	216	224	147		
0.62–0.40	210	183	202	155		
0.39–0.20	279	232	196	189		
0.19–0.15	63	56	106	66		
0.14–0.10	2	4	14	20		
<0.10	0	0	8	0		

[a]with 5% pectins, [b]Calculated according to GfE (2008): ME [MJ/kg] = 0.021503 crude protein + 0.032497 ether extract + 0.016309 starch + 0.014701 organic residue − 0.021071 crude fibre (as analysed)

Table 2. Macroscopical evaluation of the stomach mucosa *pars nonglandularis* integrity in growing pigs as previously described (Grosse Liesner et al. 2009).

Score	Macroscopic appearance
0	Smooth, shiny, no hyperkeratosis
0.5	First signs of hyperkeratosis, swelling, rim
1	Mild hyperkeratosis, swelling, first signs at the edge region
1.5	Mild to moderate hyperkeratosis, proliferation mainly along the edge region
2	Moderate hyperkeratosis, proliferations along the edge and in the central region
2.5	Moderate to severe hyperkeratosis, proliferations visible at the entire area
3	Severe hyperkeratosis
4	Erosions
5	Ulceration

to total weights and length, these parameters were evaluated relatively to the pigs' BW (organ weight/BW; jejunum length/BW). The beginning of the jejunum was defined at the *Flexura duodenojejunalis* and its end, which equals the beginning of the ileum, was set at the site from where the payer's patches appear continuously. The *Gyri centripetales* of the *Colon ascendens* were considered for "proximal colon" content, while the *Colon descendens* and *transversum* digesta were referred to as "distal colon" content. The stomach mucosa integrity of the *pars nonglandularis* was evaluated macroscopically (Grosse Liesner et al. 2009), using a modified score according to Borgelt (2015), as displayed in Table 2. The pH of the intestinal contents was determined with a daily calibrated (pH 4, pH 7) pH-metre (Beckman Coulter Inc., USA) by allowing the electrodes to stay in the digesta until a stable pH was reached. The samples were stored at −20°C until further analyses were performed to determine nutrient and energy digestibility.

2.4. Analytical methods

The nutrient contents in feed and gastrointestinal samples were measured with proximate analyses according to VDLUFA III (1976; 3.1 dry matter, 4.1.2 crude protein modified according to macro-N determination (vario Max CN), 5.1.1 ether extract, 6.1.4 crude fibre, 8.4 crude ash). The amino acid content was obtained after hydrolysis of the lyophilised samples in a 6 M aqueous hydrochloric acid (HCl) at 110°C for 24 h (Biochrom 30 Plus AA Analyzer, Biochrom Ltd., UK; VDLUFA III 4.11.1, 1976). The content of cysteine and methionine was determined after oxidation of samples with a mixture of H_2O_2 and formic acid. The concentrations of calcium (Ca), copper (Cu) and zinc (Zn) were determined by atomic absorption spectroscopy (contrAA 700, Analytic Jena AG), while phosphorous was measured using photometry at 436 nm (Ultrospec™ 2100 pro Amersham Biosciences, Amersham Biosciences Europe GmbH, Germany) according to the Vanadate-molybdate method (Gericke and Kurmies, 1952). Lignin and cellulose fractions were analysed according to Van Soest et al. (1991). Hence, amylase-treated neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) were analysed with residual ash according to VDLUFA (1976, 6.5.1, 6.5.2, 6.5.3, respectively) with an automated fibre analyser (ANKOM 2000 Automated Fiber Analyzer, USA) where fibre filter bags were used instead of filter crucibles. Total Dietary Fibre (TDF), and with it insoluble (iDF) and soluble Dietary Fibre (sDF) were analysed using a commercial enzymatic test according to the manufacturer's instruction (Megazyme K-TDF, Megazyme, Ireland).

In the feed samples, particle size distribution was determined using the dry sieving method according to VDLUFA (1976; 6.5.2). Sieves used were of the nominal mesh widths 0.063, 0.10, 0.25, 0.50, 0.63, 1.00 and 2.00 mm and were vibrated for 5 min using the vibration screening system VS 1000 (Retsch GmbH, Germany).

Jejunum, proximal and distal colon digesta were centrifuged at 16,200 × g, and viscosity was measured in the supernatant using a Brookfield DVII+ programmable viscometer (Brookfield Engineering Laboratories, Inc., USA).

2.5. Apparent nutrient digestibility

To determine the apparent ileal and total tract digestibility of nutrients, feed samples, the ileal digesta and faecal samples were lyophilised and ground (0.5 mm particle size). Concentration of the indigestible marker TiO_2 was determined as described previously (Myers et al. 2004). Apparent ileal digestibility (AID) was calculated as follows:

$$AID = 100 - \frac{TiO_2\ in\ feed\ (\%)}{TiO_2\ in\ ileum\ digesta\ (\%)} \times \frac{Nutrient\ in\ ileum\ digesta\ (\%)}{Nutrient\ in\ feed\ (\%)} \times 100$$

Apparent total tract digestibility (ATTD) was calculated as follows:

$$ATTD = 100 - \frac{TiO_2\ in\ feed\ (\%)}{TiO_2\ in\ faeces\ (\%)} \times \frac{Nutrient\ in\ faeces\ (\%)}{Nutrient\ in\ feed\ (\%)} \times 100$$

2.6. Statistical analysis

Data were analysed with the software IBM SPSS (Version 28, USA). The two-way analysis of variance (ANOVA) was applied to determine differences between groups and the post-hoc test Tukey-HSD was used to determine subgroups. The results are presented as mean values ± standard deviation. Differences were considered statistically significant at $p < 0.05$ and p-values between 0.05 and 0.1 were accepted as trends. Extreme outliers (1.5 interquartile range below 1st quartile or above 3rd quartile) were excluded.

3. Results

3.1. Diets

The particle size distribution in the diets containing coarse or finely ground hemp or apple pomace as dietary fibre source is displayed in Table 1. As anticipated, diets containing coarse fibre particles had a higher proportion of larger particles with 30.6 vs. 23.1% > 1 mm in diets containing coarse and finely ground hemp. In diets comprising coarse or finely ground apple pomace, 42.4 and 25.3% of the particles were above 1 mm, respectively. On the other hand, when the fibre-rich feedstuff was finely ground, there were relatively more smaller particles (<0.63 mm) in the diet, compared to diets with coarse fibre-rich feedstuff (hemp: 55.4 vs. 47.4%; apple pomace: 52.5 vs. 43.0%).

3.2. Animal performance

To determine the growing pigs' performance, the health status, FI and BWG were evaluated (Table 3), and all pigs were healthy throughout the animal trial. While the final pen weight was not affected by fibre type ($p = 0.892$) or fibre particle size ($p = 0.580$), the highest BWG was observed in animals fed diets containing finely ground apple pomace, while the lowest performance was observed in animals receiving the coarse apple pomace and a similar, but marginal, particle size effect was observed in animals fed diets containing dried hemp. Hence, particle size ($p = 0.018$) but not fibre type ($p = 0.161$) showed an effect, and an interaction was observed ($p = 0.040$). Also, feed intake showed a fibre type × fibre particle size interaction ($p = 0.004$). It was elevated in animals fed coarse dried hemp or finely ground apple pomace containing diets. Similarly, the observed average daily energy intake was higher in animals fed coarse hemp or fine apple pomace, which depended on fibre type ($p = 0.040$) and its interaction with fibre particle size ($p = 0.002$). This resulted in higher FCR and ECR in animals fed diets with coarse fibre-rich feedstuffs ($p = 0.012$; $p = 0.007$). Pigs fed dried hemp as dietary fibre source had firmer faeces than when apple pomace was added to the diet ($p < 0.001$).

3.3. Digesta pH and viscosity

The digesta pH was measured in stomach, jejunum, ileum, caecum, proximal and distal colon, and faeces while digesta viscosity was obtained for jejunum, proximal and distal colon. The results are summarised in Table 4. Stomach ($p = 0.064$), caecum ($p = 0.064$), distal colon ($p < 0.001$), and faeces ($p < 0.001$) pH was lowered when animals received apple pomace compared to growing pigs fed hemp containing diets. Fibre particle size did not influence the digesta pH. Interestingly, while jejunum viscosity was influenced by fibre type

Table 3. Performance of piglets ($n = 14$/group, 2 piglets/pen) fed complete diets containing dried hemp or apple pomace either coarse or finely ground for 3 weeks (mean ± standard deviation).

Fibre type	Dried hemp		Apple pomace		*p*-value		
Fibre particle size	Fine	Coarse	Fine	Coarse	Fibre type	Fibre particle size	Fibre type x fibre particle size
Pen weight start [kg]	43.2 ± 4.7	44 ± 3.3	43.4 ± 2.7	44.2 ± 3.3	0.892	0.580	0.992
Pen weight end [kg]	70.7 ± 7.5	71.0 ± 4.4	71.9 ± 6.6	66.4 ± 6.1	0.465	0.288	0.237
BWG [kg]	27.5 ± 3.4	27.1 ± 1.9	28.4 ± 4.2	22.5 ± 3.5	0.161	0.018	0.040
ADG [g]	688 ± 86	676 ± 48	711 ± 104	562 ± 88			
ADFI [kg]	1.44 ± 0.2	1.61 ± 0.1	1.56 ± 0.18	1.34 ± 0.15	0.226	0.663	0.004
FCR	2.10 ± 0.25	2.39 ± 0.21	2.21 ± 0.17	2.41 ± 0.29	0.496	0.012	0.636
Faecal score (median)	4	4	3	3	<0.001	0.258	0.704

ADFI: average daily feed intake, ADG: average daily gain, BWG: bodyweight gain, FCR: feed conversion ratio.

Table 4. Organ weight and length as well as digesta pH in piglets ($n = 8$/group) fed complete diets containing dried hemp or apple pomace either coarse or finely ground for 3 weeks (mean ± standard deviation).

Fibre type		Dried hemp		Apple pomace		*p*-value		
Fibre particle size	GIT section	Fine	Coarse	Fine	Coarse	Fibre type	Fibre particle size	Fibre type× particle size
BW at slaughter [kg]		36.3 ± 5.5	34.7 ± 2.9	35.4 ± 4.7	34.9 ± 2.6			
Stomach score		0.75 ± 0.38	0.56 ± 0.42	0.25 ± 0.53	0.88 ± 1.30	0.729	0.421	0.141
pH	stomach	5.17 ± 2.40	4.44 ± 1.21	4.10 ± 1.32	3.73 ± 1.29	0.064	0.192	0.976
	jejunum	6.36 ± 0.37	6.44 ± 0.27	6.23 ± 0.94	6.51 ± 0.75	0.903	0.441	0.674
	ileum	6.35 ± 0.49	6.64 ± 0.4	6.24 ± 0.57	6.52 ± 0.82	0.597	0.175	0.969
	caecum	6.47 ± 1.20	5.95 ± 0.13	5.74 ± 0.22	5.65 ± 0.24	0.046	0.224	0.385
	proximal colon	6.18 ± 0.45	6.19 ± 0.15	6.00 ± 0.89	5.86 ± 0.35	0.204	0.730	0.683
	distal colon	6.22 ± 0.25	6.30 ± 0.13	5.63 ± 0.14	5.76 ± 0.21	<0.001	0.149	0.736
	faeces	7.08 ± 0.61	6.82 ± 0.39	6.02 ± 0.7	6.06 ± 0.26	<0.001	0.529	0.418
Viscosity [mPa•s]	jejunum	1.32 ± 0.23	1.40 ± 0.17	6.26 ± 2.24	5.29 ± 3.04	<0.001	0.512	0.437
	proximal colon	1.61 ± 0.26	1.90 ± 0.34	1.50 ± 0.4	2.20 ± 1.24	0.691	0.053	0.422
	distal colon	2.69 ± 1.36	2.73 ± 1.08	1.79 ± 0.73	4.38 ± 2.92	0.543	0.038	0.044
Relative organ weight [g/kg BW]	pancreas	2.08 ± 0.14	2.01 ± 0.55	2.32 ± 0.29	2.37 ± 0.48	0.045	0.920	0.658
	liver	29.1 ± 3.3	29.0 ± 2.8	29.3 ± 2.9	29.0 ± 1.4	0.881	0.851	0.903
Jejunum length [m]		13.1 ± 1.4	12.5 ± 1.3	13.8 ± 1.1	13.8 ± 1.8	0.042	0.525	0.574
GIT relative organ weight: empty [g/kg BW]	stomach	22.2 ± 5.9	18.1 ± 5.7	38.3 ± 7.3	44.2 ± 18.6	<0.001	0.811	0.205
	Jejunum	45.8 ± 3.6	48.4 ± 5.3	52.7 ± 3.7	51.6 ± 7.2	0.010	0.702	0.312
	Ileum	12.0 ± 2.2	9.4 ± 2.5	12.8 ± 3.9	12.5 ± 3.8	0.099	0.212	0.336
	Caecum	8.7 ± 2.8	7.9 ± 2.6	10.3 ± 4.4	10.1 ± 3.4	0.118	0.677	0.822
	Colon	29.3 ± 5.5	25.9 ± 5.8	23.6 ± 7.8	22.3 ± 8.5	0.074	0.361	0.672
GIT: relative intestinal content weight [g/kg BW]	stomach	14.4 ± 6	10.3 ± 6	30.7 ± 7	34.5 ± 20	<0.001	0.765	0.564
	jejunum	12.5 ± 1.7	11.5 ± 3.3	18.3 ± 2.4	15.6 ± 4.2	<0.001	0.166	0.332
	ileum	4.37 ± 0.28	2.80 ± 1.81	6.14 ± 3.3	4.77 ± 2.5	0.070	0.112	0.991
	caecum	6.00 ± 2.57	5.01 ± 2.29	7.62 ± 4.13	6.79 ± 3.39	0.257	0.564	0.895
	colon	19.5 ± 5.3	17.2 ± 4.7	14.8 ± 6.2	12.4 ± 7.2	0.100	0.332	0.613

BW: bodyweight, GIT: gastrointestinal tract.

($p < 0.001$), fibre particle size influenced viscosity in the colon (proximal: $p = 0.053$; distal: $p = 0.038$). Hence, growing pigs fed apple pomace had higher jejunum digesta viscosity compared to hemp, while larger dietary fibre particles led to higher viscosity in the hindgut. Also, an interaction of fibre type × particle size was observed in the distal colon ($p = 0.044$). Here, the highest viscosity was observed in growing pigs fed coarse apple pomace.

3.4. *Organ weight and length*

Organ weights, gut content and jejunum length are displayed in Table 4. No difference in liver weight was observed. The relative pancreas weight was higher in animals from the apple pomace than in the hemp group ($p = 0.045$). Similarly, the jejunum was longer in animals fed diets containing apple pomace compared to hemp ($p = 0.042$). These animals also had more content in their stomach ($p <$

0.001), jejunum ($p < 0.001$), and ileum ($p = 0.070$), but less digesta in the colon ($p = 0.014$). Relative to BW, the empty stomach ($p < 0.001$), jejunum ($p = 0.001$) and ileum (trend, $p = 0.099$) weights were lower in the hemp group, while the relative empty colon weight tended to be lower in animals fed diets containing apple pomace ($p = 0.074$). Fibre particle size had no influence on the relative organ weights.

3.5. Stomach mucosa integrity

The integrity of the *pars nonglandularis* of the stomach was evaluated (Table 4). Beside one animal receiving coarse apple pomace, there were only mild hyperkeratosis and no differences were observed depending on fibre particle size or type.

3.6. Apparent nutrient digestibility

The digestibility of chosen nutrients was calculated, and results are displayed in Table 5. Fibre source and, to a lower extent, fibre particle size influenced protein and amino acid digestibility. However, this was mainly true for ATTD, while AID was not affected by fibre source and fibre particle size. The only exception was observed regarding valine and proline AID. Valine showed a higher AID when hemp was applied in the diet compared to apple pomace ($p = 0.043$) and fine compared to coarse fibre particle size tended to enhance valine AID as well ($p = 0.071$), with a fibre source × fibre particle size interaction ($p = 0.005$). Proline was only affected by fibre particle size ($p = 0.058$). Crude protein and amino acid ATTD on the other hand was increased in the growing pigs fed diets containing hemp ($p \leq 0.011$). This led to a lower nitrogen concentration in the faeces from these animals (data not shown, $p < 0.001$). Fibre particle size again only influenced valine ATTD ($p = 0.016$), while a fibre source × fibre particle size interaction was observed for crude protein ($p = 0.027$) and valine ($p = 0.001$).

While crude ash digestibility did not differ between treatments, some variations were observed for the mineral digestibility. Regarding Zn, both AID and ATTD increased in animals receiving dried hemp ($p = 0.016$: $p = 0.029$), while diets containing apple pomace showed higher Ca AID. The opposite was observed for Cu AID, which was enhanced in animals fed finely ground dried hemp or coarse apple pomace ($p = 0.045$).

4. Discussion

The present study investigated the inclusion of coarse or finely ground apple pomace or hemp to the diets of growing pigs in regards to pig performance and nutrient digestibility. It is well known that dietary fibre can have a positive effect on gut health (Grześkowiak et al. 2023), but knowledge on the impact of fibre particle size is scarce in pigs.

It is well known that finely ground feed results in higher nutrient digestibility and performance (Acosta et al. 2020), but is also a risk factor for the prevalence of ulcerations of the stomach mucosa (Mößeler et al. 2010; Cappai et al. 2013). In horses, gastric ulcer is observed in individuals receiving diets rich in starch and sugar, while fibre-rich diets appear to be protective (Luthersson et al. 2019). It would be of interest to know if fibre-rich diets can assert a certain protective feature in pigs and how the particle size of the

Table 5. Nutrient digestibility in piglets ($n = 8$/group) fed complete diets containing dried hemp or apple pomace either coarse or finely ground for 3 weeks (mean ± standard deviation).

Fibre Type	Dried hemp		Apple pomace		*p*-value		
Particle size	Fine	Coarse	Fine	Coarse	Fibre type	Fibre particle size	Fibre type × particle size
AID [%]							
Crude protein	67.8 ± 10.3	61.6 ± 16.6	66.0 ± 11.2	62.0 ± 12.3	0.517	0.869	0.345
Total amino acids	76.2 ± 7.5	70.7 ± 12.7	73.0 ± 9.9	71.5 ± 9.5	0.427	0.817	0.575
Indispensable amino acids							
Arginine	83.1 ± 4.8	76.0 ± 12.7	81.9 ± 6.6	80.8 ± 7.4	0.783	0.734	0.623
Histidine	77.3 ± 7.5	71.3 ± 13.9	71.9 ± 11.7	72.8 ± 8.2	0.257	0.655	0.690
Isoleucine	76.2 ± 7.1	70.7 ± 12.9	75.8 ± 8.2	75.3 ± 7.4	0.897	0.736	0.595
Leucine	75.9 ± 8.6	71.1 ± 13.8	71.9 ± 12.2	73.6 ± 8.2	0.506	0.515	0.656
Lysine	82.2 ± 5.5	72.9 ± 13.4	80.4 ± 7.6	78.7 ± 7.6	0.780	0.821	0.636
Methionine	84.5 ± 6.0	77.5 ± 12.9	83.0 ± 7.1	83.8 ± 4.9	0.799	0.545	0.642
Phenylalanine	77.8 ± 7.3	73.4 ± 12.1	75.8 ± 9.8	76.3 ± 7.1	0.749	0.612	0.608
Threonine	72.0 ± 9.5	64.6 ± 15.4	69.5 ± 11.6	69.8 ± 7.9	0.831	0.842	0.694
Valine	83.8 ± 5.4	77.4 ± 12.2	83.8 ± 6.7	73.4 ± 7.4	0.043	0.071	0.005
Dispensable amino acids							
Alanine	70.2 ± 10.3	61.7 ± 17.7	66.9 ± 12.4	67.0 ± 10.5	0.734	0.832	0.716
Aspartic acid	77.1 ± 6.3	68.2 ± 13.2	74.9 ± 7.7	72.1 ± 7.8	0.517	0.697	0.550
Cysteine	65.1 ± 12.3	59.1 ± 17.5	62.6 ± 13.1	54.9 ± 13.6	0.193	0.968	0.369
Glutamic acid	79.1 ± 6.1	71.4 ± 12.5	76.2 ± 7.8	74.9 ± 9.5	0.476	0.803	0.828
Glycine	59.1 ± 11.6	51.6 ± 20.7	48.9 ± 19.5	53.7 ± 6.0	0.217	0.807	0.893
Proline	69.6 ± 10.1	61.1 ± 19.6	60.1 ± 13.4	63.5 ± 11.8	0.058	0.201	0.879
Serine	70.7 ± 9.7	66.1 ± 13.1	68.9 ± 11.9	69.7 ± 7.8	0.870	0.683	0.596
Tyrosine	72.7 ± 9.2	68.1 ± 14.1	70.4 ± 11.8	70.1 ± 9.5	0.651	0.633	0.503
Minerals							
Ca	41.8 ± 11.9	52.5 ± 15.7	76.6 ± 8.9	76.8 ± 16.6	<0.001	0.305	0.325
Zn	15.8 ± 20.3	17.7 ± 24.0	0.6 ± 13.2	−9.7 ± 33.4	0.016	0.222	0.998
Cu	62.9 ± 11.7	41.4 ± 38.7	53.6 ± 8.0	56.4 ± 8.4	0.823	0.103	0.045
ATTD [%]							
Crude protein	74.2 ± 3.2	75.6 ± 3.2	67 ± 3.2	64.9 ± 8	<0.001	0.440	0.027
Total amino acids	81.3 ± 2.5	80.9 ± 3.3	74.6 ± 2.6	74.9 ± 8	<0.001	0.484	0.764
Indispensable amino acids							
Arginine	86 ± 2.1	85.3 ± 2.7	81.4 ± 1.7	81.7 ± 4.2	0.001	0.497	0.961
Histidine	84.1 ± 2	83.8 ± 3	76.2 ± 1.6	78.1 ± 5.0	<0.001	0.200	0.719
Isoleucine	76.1 ± 3.4	75.4 ± 4.8	70.9 ± 3.7	71.4 ± 6.2	0.009	0.421	0.768
Leucine	79 ± 2.8	80 ± 1.8	72.9 ± 2.9	74.8 ± 5.5	0.003	0.241	0.879
Lysine	82.3 ± 2.7	82.3 ± 3.2	75.4 ± 2.9	75.3 ± 5.7	<0.001	0.425	0.672
Methionine	81.9 ± 2.6	83 ± 0.8	72.4 ± 2.9	72.5 ± 3.0	<0.001	0.407	0.689
Phenylalanine	80.2 ± 2.5	80.9 ± 1.9	75.6 ± 2.9	76.7 ± 5.2	0.011	0.332	0.983
Threonine	79.8 ± 4.2	77.8 ± 3.6	70.8 ± 3.4	72.1 ± 6.4	0.001	0.601	0.651
Valine	85.8 ± 2	86.3 ± 2.6	83.3 ± 1.4	72.0 ± 6.1	<0.001	0.016	0.001
Dispensable amino acids							
Alanine	73.9 ± 3.7	73.6 ± 4.8	64.5 ± 3.6	66.1 ± 8.0	0.001	0.318	0.973
Aspartic acid	80.7 ± 3.8	78.9 ± 3.4	73.8 ± 1.8	71.1 ± 6.7	0.001	0.566	0.562
Cysteine	80.1 ± 2.6	79.7 ± 0.9	67.1 ± 1.7	68.9 ± 3.3	<0.001	0.413	0.266
Glutamic acid	85.1 ± 2.3	84.6 ± 3.1	80.0 ± 1.7	80.7 ± 4.6	0.001	0.410	0.955
Glycine	74.3 ± 3.2	74.3 ± 4.2	66.5 ± 3.1	67.8 ± 7.4	0.001	0.269	0.905
Proline	81.3 ± 2.4	81.6 ± 3.1	70.6 ± 2.8	74.1 ± 5.7	<0.001	0.099	0.528
Serine	80.7 ± 3.3	79.3 ± 3.4	73.9 ± 2.8	75.4 ± 5.7	0.003	0.442	0.641
Tyrosine	76.2 ± 3.1	76.3 ± 4.3	69.4 ± 4.1	69.5 ± 6.7	0.001	0.443	0.632
Minerals							
Ca	62.3 ± 15.3	63.8 ± 19.4	62.5 ± 18.4	59.5 ± 27.0	0.786	0.815	0.851
Zn	20.3 ± 5.0	17.1 ± 6.7	14.5 ± 8.5	10.0 ± 11.5	0.029	0.171	0.893
Cu	65.5 ± 4.2	67.7 ± 4.7	67.1 ± 3.6	66.8 ± 5.6	0.754	0.831	0.727

AID: apparent ileal digestibility; ATTD: apparent total tract digestibility.

fibre-rich feedstuff influences this. Ideally, starch- and protein-rich components in the diet could be finely ground to assure maximum utilisation, while the type and particle size of fibre-rich ingredients would assure gastric health. We could show that apple pomace led to lower stomach pH than hemp inclusion to the diet, while no differences were observed regarding fibre particle size. However, all measured stomach pH-levels were within the physiological levels (Grosse Liesner et al. 2009). A low gastric pH can be helpful to reduce survival of potentially pathogenic bacteria from the environment (Szabó et al. 2023) but also poses a risk factor for gastric ulcer (Peralvo-Vidal et al. 2021). Overall, the integrity of the *pars nonglandularis* of the stomach was not affected in our study. This suggests that all dietary fibre options led to a favourable stomach health. On the other hand, the relatively short feeding interval of 3 weeks might be the reason that no differences were observed and longer feeding trials should follow to confirm these results.

While fibre type did not change the growing pigs' performance in our trial, BWG was increased in growing pigs fed finely ground hemp or apple pomace. As FI stayed unaffected by dietary fibre particle size, the FCR and ECR were lower in growing pigs fed finely ground fibre-rich feedstuff in their diet. It was previously stated that larger particle size of fibre-rich feedstuff can increase the SCFA formation in the hindgut (Molist et al. 2012). Therefore, better performance was expected when feeding the larger fibre particle size and a more soluble fibre source. As the opposite (particle size) or no effect (fibre source) was observed in our study, this hypothesis could not be confirmed. A possible explanation could be a higher nutrient digestibility in the small intestine. This would be in accordance with studies investigating the feed particle size of the entire feed (Borgelt 2015; Acosta et al. 2020), as smaller particles offer larger surface for enzymes. However, these studies did consider the entire feed particle size rather than only the fibre-rich feedstuff, and we could not detect differences in protein AID depending on the fibre particle size. The negative effect on FI in pigs fed coarse apple pomace observed in our study could be explained by the fact that it contained hard and sharp particles and that the texture was not appreciated by the growing pigs. It was previously shown that the hardness of feed components and the chewing work can reduce the preference for the feed (Solà-Oriol et al. 2009), which could explain these results. Another explanation could be that the larger particles, together with the swelling capacity of apple pomace, may have increased satiety and therefore reduced FI.

Our results suggest that finely ground apple pomace might be favourable around weaning, when stomach pH should be low to protect the immunologically immature piglets against potentially harmful bacteria from the environment (Markowska-Daniel et al. 2010; Szabó et al. 2023). Finely ground hemp, resulting in a higher stomach pH, might instead be preferred in fattening pigs, considering gastric health as an important factor for pig productivity and welfare (Szabó et al. 2023). In the present study, different fibre types and the fibre-rich feedstuff particle size were compared against each other but not against a control group without or with low concentrations of dietary fibre. This should be investigated in the future.

Diets high in dietary fibre are generally considered to reduce performance in pigs. This is explained by the dilution effect of energy and nutrients but can be avoided by appropriate diet balancing (Röhe and Zentek 2021). Furthermore, digestibility of the nutrients can be reduced due to decreased enzymatic activity, impaired absorption and increased endogenous secretion (Blank et al. 2012). High digesta viscosity can also be a reason for decreased nutrient digestibility, when feeding diets with high concentrations of soluble dietary fibre (Bach Knudsen et al. 1991). Additionally, low acceptance of fibre-rich diets due to low palatability may reduce FI and thus performance in pigs (Saliu et al. 2022). To avoid the bias of palatability, the fibre type was chosen based on the results from a cafeteria trial with sows, where apple pomace and dried hemp were the preferred options (Saliu et al. 2022). It was previously shown that the type of dietary fibre has an impact on nutrient digestibility and that soluble dietary fibre may have a more severe negative effect than insoluble dietary fibre (Cherbut et al. 1990; Bach Knudsen et al. 1991; Blank et al. 2012). Interestingly, while this was true for Zn AID and ATTD in the present study, the opposite was observed regarding Ca AID. The low apparent digestibility of Zn might be explained by the higher jejunum digesta viscosity. Simultaneously, pancreas weight and jejunum length were increased in animals fed the apple pomace containing diets. This is a common consequence to compensate for the reduced nutrient digestibility due to the high digesta viscosity. Another explanation might be that transit time was reduced, as the gut fill of the proximal gastrointestinal tract was higher in these animals, compared to the pigs fed diets with hemp. As apple pomace has less bulking effect than dried hemp, the stimulation of intestinal contraction might be reduced and lead to slower transportation of the digesta (Schulze-Delrieu et al. 1991; Wilke et al. 2021). Differences in AID digestibility might also be explained by changes in transit time, lower endogenous secretion or enlarged intestinal surface (Guixin et al. 1995). While transit time and endogenic losses were not investigated in our study, the pancreas and gut weight were evaluated, but no fibre particle size depending effects were observed.

Crude protein and amino acid AID did not differ between feeding groups. In contrast, crude protein and amino acid ATTD were higher in animals fed diets containing dried hemp instead of apple pomace. This supports our hypothesis that fibre source if a higher proportion of soluble dietary fibres may increase viscosity and thereby reduce nutrient digestibility in the small intestines (Bach Knudsen et al. 1991). It also led to lower faecal nitrogen excretion, which can be favourable for the environmental impact, subject to the condition that urinary nitrogen excretion is comparable between diets (Millet et al. 2018). As urine was not investigated in the current study, the impact of fibre source on total nitrogen excretion cannot be evaluated, and further research is warranted.

A previous study showed that besides a reduced nutrient digestibility, hindgut fermentation was altered with increased viscosity, as the SCFA composition showed lower propionate and butyrate proportions (Petry et al. 2021). Although the viscosity in jejunum digesta of the growing pigs fed apple pomace was high, even compared to piglets fed 30% rye in their diets (Ellner et al. 2021), colon digesta samples showed relatively low viscosity in the present study. This could be the explanation for the equal performance when feeding hemp or apple pomace containing diets. Soluble dietary fibres are known to be easily fermented by the intestinal microbiota, which produce short chain fatty acids (SCFA) that can be used for energy metabolism by the host (Grześkowiak et al. 2023). Growing pigs fed hemp containing diets had more digesta in their hindgut than the pigs fed diets with apple pomace. Here, it can be assumed that hemp led to a slower fermentation and thereby more organic matter remaining in the colon.

Growing pigs fed diets containing apple pomace instead of dried hemp had softer faeces. This was not surprising, as moister faeces was previously reported when pigs were fed diets containing a fibre source with a higher portion of soluble dietary fibre, such as apple pomace (Grześkowiak et al., 2002; Dufourny et al. 2021).

Besides the fibre source, secondary plant compounds in the fibre source may have influenced the outcome of the study as well. Hemp contains unsaturated *n*-3 fatty acids, which can reduce inflammatory reactions in the animals and thereby enhance performance (Della Rocca and Di Salvo 2020). Furthermore, it was claimed that hemp contains antioxidative and antimicrobial compounds, which also can improve animal performance and health (Crini et al. 2020). Apple pomace is rich in antioxidants, such as quercetin glycosides and phloridzin, and appreciated in human nutrition due to its ability to scavenge free radicals (Lyu et al. 2020). This could have reduced subclinical inflammations in the growing pigs in our study and thereby avoided energy to be lost for healing processes, promoting health and performance. However, none of these compounds were analysed in our study and, hence, we can only speculate how they contributed to the observed results.

Both fibre type and particle size influenced performance and nutrient digestibility. Hence, feed intake and BWG were enhanced, and FCR reduced when fibre rich feedstuff was finely ground. The stomach integrity was maintained by all fibre type and fibre particle size options. Growing pigs fed diets containing apple pomace compared to dried hemp had heavier pancreas, stomach and jejunum. Additionally, their jejunum was longer. The AID of calcium was increased when diets contained apple pomace, while zinc AID and ATTD were improved when diets contained dried hemp.

5. Conclusion

Our results suggest that both chemical and physical characteristics of fibre rich feedstuff influence performance and nutrient digestibility in growing pigs. Thus, a future fibre evaluation system should consider both fibre solubility and fibre particle size.

Acknowledgments

The authors want to thank Anett Kriesten, Claudia Kipar, Luisa Ebersbach, Katharina Schröter, Petra Huck and Marita Eitinger for support during the laboratory analyses. Furthermore, we thank all animal caretakers of the Institute of Animal Nutrition at the Freie Universität Berlin for great support during the animal experiment.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Eva-Maria Saliu http://orcid.org/0000-0003-2228-8546
Johannes Schulze Holthausen http://orcid.org/0000-0002-8675-9258
Volker Wilke http://orcid.org/0000-0003-0443-7042

Data availability statement

Raw data were generated at the Institute of Animal Nutrition, Freie Universität Berlin. Derived data supporting the findings of this study are available from the corresponding author ES on request.

References

Acosta JA, Petry AL, Gould SA, Jones CK, Stark CR, Fahrenholz A, Patience JF. 2020. Effects of grinding method and particle size of wheat grain on energy and nutrient digestibility in growing and finishing pigs. Transl Anim Sci. 4:682–693. doi: 10.1093/tas/txaa062.

Bach Knudsen KE, Jensen BB, Andersen JO, Hansen I. 1991. Gastrointestinal implications in pigs of wheat and oat fractions. 2. Microbial activity in the gastrointestinal tract. Br J Nutr. 65:233–248. doi: 10.1079/bjn19910083.

Blank B, Schlecht E, Susenbeth A. 2012. Effect of dietary fibre on nitrogen retention and fibre associated threonine losses in growing pigs. Arch Anim Nutr. 66:86–101. doi: 10.1080/1745039x.2012.663669.

Borgelt L. 2015. Einflüsse einer zweistufigen Vermahlung in der Mischfutterproduktion auf die Leistung und Gesundheit von Absetzferkeln. Hannover: Tierärztliche Hochschule. DVG. Hannover. ISBN:978-386-345-295-7.

Cappai MG, Picciau M, Pinna W. 2013. Ulcerogenic risk assessment of diets for pigs in relation to gastric lesion prevalence. BMC Vet Res. 9:36. doi: 10.1186/1746-6148-9-36.

Cherbut C, Albina E, Champ M, Doublier JL, Lecannu G. 1990. Action of guar gums on the viscosity of digestive contents and on the gastrointestinal motor function in pigs. Digestion. 46:205–213. doi: 10.1159/000200347.

Crini G, Lichtfouse E, Chanet G, Morin-Crini N. 2020. Applications of hemp in textiles, paper industry, insulation and building materials, horticulture, animal nutrition, food and beverages, nutraceuticals, cosmetics and hygiene, medicine, agrochemistry, energy production and environment: a review. Environ Chem Lett. 18:1451–1476. doi: 10.1007/s10311-020-01029-2.

Della Rocca G, Di Salvo A. 2020. Hemp in veterinary medicine: from feed to drug. Front Vet Sci. 7:387. doi: 10.3389/fvets.2020.00387.

Dufourny S, Antoine N, Pitchugina E, Delcenserie V, Godbout S, Douny C, Scippo M-L, Froidmont E, Rondia P, Wavreille J, et al. 2021. Apple pomace and performance, intestinal morphology and microbiota of weaned piglets—a weaning strategy for gut health? Microorganisms. 9:572. doi: 10.3390/microorganisms9030572.

Edwards WM, van der Sluis GT, Stevermer EJ. 1989. Determinants of profitability in farrow-to-finish swine production. Appl Eco Perspectives Pol. 11:17–25. doi: 10.1093/aepp/11.1.17.

Ellner C, Martínez-Vallespín B, Saliu E-M, Zentek J, Röhe I. 2021. Effects of cereal and protein source on performance, apparent ileal protein digestibility and intestinal characteristics in weaner piglets. Arch Anim Nutr. 75:263–277. doi: 10.1080/1745039X.2021.1958647.

Faugno S, Piccolella S, Sannino M, Principio L, Crescente G, Baldi GM, Fiorentino N, Pacifico S. 2019. Can agronomic practices and cold-pressing extraction parameters affect phenols and polyphenols content in hempseed oils? Ind Crops Prod. 130:511–519. doi: 10.1016/j.indcrop.2018.12.084.

Gericke S, Kurmies B. 1952. Colorimetrische Bestimmung der Phosphorsäure mit Vanadat-Molybdat. Z. Anal. Chem. 137:15–22. doi: 10.1007/BF00452421.

GfE. 2006. Empfehlungen zur Energie- und Nährstoffversorgung von Schweinen. DLG-Verlag Frankfurt am Main.

GfE. 2008. Prediction of metabolisable energy of compound feeds for pigs. Proceedings of the society of nutrition physiology. Vol. 17. DLG-Verlag Frankfurt am Main. p. 199–204.

Grosse Liesner V, Taube V, Leonhard-Marek S, Beineke A, Kamphues J. 2009. Integrity of gastric mucosa in reared piglets – effects of physical form of diets (meal/pellets), pre-processing grinding (coarse/fine) and addition of lignocellulose (0/2.5 %). J Anim Physiol Anim Nutr (Berl). 93:373–380. doi: 10.1111/j.1439-0396.2008.00871.x.

Grześkowiak Ł, Saliu EM, Martínez-Vallespín B, Aschenbach JR, Brockmann GA, Fulde M, Hartmann S, Kuhla B, Lucius R, Metges CC, et al. 2023. Dietary fiber and its role in performance, welfare, and health of pigs. Anim Health Res Reviews: 1–29. doi: 10.1017/S1466252322000081.

Grześkowiak Ł, Saliu EM, Martínez-Vallespín B, Wessels AG, Männer K, Vahjen W, Zentek J. 2002. Fiber composition in sows' diets modifies Clostridioides difficile colonization in Their offspring. Curr Microbiol. 79:154. doi: 10.1007/s00284-022-02848-y.

Guixin Q, Verstegen MWA, Bosch MW. 1995. Variation of digestive capacity between genetically different pig populations: a review. J Anim Physiol Anim Nutr (Berl). 73:233–242. doi: 10.1111/j.1439-0396.1995.tb00423.x.

Krogh U, Bruun TS, Amdi C, Flummer C, Poulsen J, Theil PK. 2015. Colostrum production in sows fed different sources of fiber and fat during late gestation. Can J Anim Sci. 95:211–223. doi: 10.4141/cjas-2014-060.

Luthersson N, Bolger C, Fores P, Barfoot C, Nelson S, Parkin T, Harris P. 2019. Effect of changing diet on gastric ulceration in exercising horses and ponies after cessation of omeprazole treatment. J Equine Vet Sci. 83:102742. doi: 10.1016/j.jevs.2019.05.007.

Lyu F, Luiz SF, Azeredo DRP, Cruz AG, Ajlouni S, Ranadheera CS. 2020. Apple pomace as a functional and healthy ingredient in food products. A review. Processes. 8:319. doi: 10.3390/pr8030319.

Markowska-Daniel I, Pomorska-Mól M, Pejsak Z. 2010. Dynamic changes of immunoglobulin concentrations in pig colostrum and serum around parturition. Pol J Vet Sci. 13:21–27.

Mertens DR. 1997. Creating a system for meeting the fiber requirements of dairy cows. J Dairy Sci. 80:1463–1481. doi: 10.3168/jds.S0022-0302(97)76075-2.

Millet S, Aluwé M, Van den Broeke A, Leen F, De Boever J, De Campeneere S. 2018. Review: pork production with maximal nitrogen efficiency. Animal. 12:1060–1067. doi: 10.1017/S1751731117002610.

Molist F, Manzanilla EG, Perez JF, Nyachoti CM. 2012. Coarse, but not finely ground, dietary fibre increases intestinal Firmicutes: bacteroidetes ratio and reduces diarrhoea induced by experimental infection in piglets. Br J Nutr. 108:9–15. doi: 10.1017/S0007114511005216.

Molist F, van Oostrum M, Perez JF, Mateos GG, Nyachoti CM, van der Aar PJ. 2014. Relevance of functional properties of dietary fibre in diets for weanling pigs. Anim Feed Sci Tech. 189:1–10. doi: 10.1016/j.anifeedsci.2013.12.013.

Mößeler A, Köttendorf S, Große Liesner V, Kamphues J. 2010. Impact of diets' physical form (particle size; meal/pelleted) on the stomach content (dry matter content, pH, chloride concentration) of pigs. Livest Sci. 134:146–148. doi: 10.1016/j.livsci.2010.06.121.

Musacchi S, Serra S. 2018. Apple fruit quality: overview on pre-harvest factors. Sci Hortic (Amsterdam). 234:409–430. doi: 10.1016/j.scienta.2017.12.057.

Muscat A, de Olde EM, de Boer IJM, Ripoll-Bosch R. 2020. The battle for biomass: a systematic review of food-feed-fuel competition. Global Food Secur. 25:100330. doi: 10.1016/j.gfs.2019.100330.

Myers WD, Ludden PA, Nayigihugu V, Hess BW. 2004. Technical note: a procedure for the preparation and quantitative analysis of samples for titanium dioxide. J Anim Sci. 82:179–183. doi: 10.2527/2004.821179x.

Peralvo-Vidal JM, Weber NR, Nielsen JP, Bache JK, Haugegaard S, Pedersen AØ. 2021. Risk factors for gastric ulceration in nursery pigs. Prev Vet Med. 189:105298. doi: 10.1016/j.prevetmed.2021.105298.

Petry AL, Huntley NF, Bedford MR, Patience JF. 2021. The influence of xylanase on the fermentability, digestibility, and physicochemical properties of insoluble corn-based fiber along the gastrointestinal tract of growing pigs. J Anim Sci. 99. doi: 10.1093/jas/skab159.

Pieszka M, Szczurek P, D B-Ł, Migdał W, Pieszka M, Gogol P, Jagusiak W. 2017. The effect of dietary supplementation with dried fruit and vegetable pomaces on production parameters and meat quality in fattening pigs. Meat Sci. 126:1–10. doi: 10.1016/j.meatsci.2016.11.016.

Röhe I, Zentek J. 2021. Lignocellulose as an insoluble fiber source in poultry nutrition: a review. J Anim Sci Biotechnol. 12:82. doi: 10.1186/s40104-021-00594-y.

Saliu E, Schulze Holthausen J, Zentek J. 2022. Sows' preference for fibre-rich feedstuffs and the impact of fibre particle size on feed intake duration, faecal consistency and short-chain fatty acids in faeces from sows. In: Liesegang A, editor. 26th congress of the European college of veterinary and comparative nutrition, 6–8 September 2022. Basel: Steinemann Print AG.

Schulze-Delrieu K, Brown BP, Custer-Hagen T. 1991. Contraction and accommodation of guinea pig duodenum in vitro. Am J Physiol. 261:G364–372. doi: 10.1152/ajpgi.1991.261.2.G364.

Small E, Cronquist A. 1976. A practical and natural taxonomy for Cannabis. Taxon. 25:405–435. doi: 10.2307/1220524.

Solà-Oriol D, Roura E, Torrallardona D. 2009. Feed preference in pigs: relationship with feed particle size and texture. J Anim Sci. 87:571–582. doi: 10.2527/jas.2008-0951.

Szabó C, Kachungwa Lugata J, Adsv O. 2023. Gut health and influencing factors in pigs. Animals. 13:1350. doi: 10.3390/ani13081350.

Tedeschi A, Cerrato D, Menenti M. 2022. Is the potential for multi-functional use of industrial hemp greater than maize under saline conditions? Sustainability. 14:15646. doi: 10.3390/su142315646.

Vendruscolo F, Albuquerque PM, Streit F, Esposito E, Ninow JL. 2008. Apple pomace: a versatile substrate for biotechnological applications. Crit Rev Biotechnol. 28:1–12. doi: 10.1080/07388550801913840.

Vonapartis E, Aubin M-P, Seguin P, Mustafa AF, Charron J-B. 2015. Seed composition of ten industrial hemp cultivars approved for production in Canada. J Food Compos Anal. 39:8–12. doi: 10.1016/j.jfca.2014.11.004.

Wilke V, Grone R, von Felde A, Abd El-Wahab A, Wolf P, Kamphues J. 2021. Effects of increasing dietary rye levels on physicochemical characteristics of digesta and its impact on stomach emptying as well as the formation of 'doughballs' in stomachs of young pigs. J Anim Physiol Anim Nutr (Berl). 105:19–25. doi: 10.1111/jpn.13549.

Zebeli Q, Aschenbach JR, Tafaj M, Boguhn J, Ametaj BN, Drochner W. 2012. Invited review: role of physically effective fiber and estimation of dietary fiber adequacy in high-producing dairy cattle. J Dairy Sci. 95:1041–1056. doi: 10.3168/jds.2011-4421.