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In vitro studies to characterise different physico-chemical properties of some feed grains and their impact in monogastric nutrition

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ABSTRACT
Characterisation of the variations in physico-chemical properties of grains may help to improve the feeding value of grains for animal nutrition. Thus, this study aimed to obtain more extensive quantitative ideas concerning different physico-chemical properties of wheat, hybrid rye, and barley. The samples were ground in a hammer mill using screen size of 1, 3, and 6 mm, respectively. The cumulative mean particle distribution at >1.0 mm of the ground grains showed significant differences between wheat and hybrid rye (4.63 and 9.13%, respectively). At dry sieve analysis of 6 mm screen size, hybrid rye had significantly higher mean particle size distribution of >1.0 mm (26.8%) than for ground wheat and barley. Ground wheat using a 1 mm mesh sieve had the lowest water holding capacity and swelling capacity (1.89 g H_2O/g dry matter (DM); $p = .001$ and 1.33 mL H_2O/g DM; $p = .021$, respectively) compared to hybrid rye and barley. Ground hybrid rye using a 1 mm mesh sieve had the significantly highest extract viscosity (6.22 mPa s). Ground wheat had the lowest ($p < .001$) corrected sediment rate. In general, ground hybrid rye had always a higher feed particle size >1 mm regardless of the grinding size. Ground wheat had the lowest water holding capacity irrespective of the grinding mesh sieve. Finally, hybrid rye in general is characterised by high extract viscosity (6.22 mPa s at 1 mm grinding size), which decreased with coarser grinding (3.75 and 3.10 mPa s at 3 and 6 mm, respectively).

HIGHLIGHTS
- Particle size distribution is directly affected by the grinding process.
- Water holding capacity and swelling capacity are two complementary measurements.
- Extract viscosity seems to be affected by grinding; however, the sedimentation rate is influenced by the grain type.

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Cereals; particle size; hydration capacity; viscosity; sedimentation

Introduction

Global food production has risen dramatically in the last 60 years due to agricultural expansion and intensification (Arenas-Corraliza et al. 2019). Cereal grains and their by-products are an important nutritive component worldwide (Kowieska et al. 2011; Papageorgiou and Skendi 2018). Therefore, special attention is given to intensive cultivation of cereal grains, especially those adapted to various climatic and environmental conditions such as rye (Bederska-Łojewska et al. 2017). Currently, rye grain is also receiving growing interest, being included in foods, mostly as raw material for bread (Kamal-Eldin et al. 2008; Deleu et al. 2020).

One of the most important factors that determine feed utilisation is the particle size distribution (Rojas and Stein 2017; Kiarie and Mills 2019). Particle size reduction generally includes the grinding step with a hammer mill or roller mill (Kiarie and Mills 2019). There are numerous reviews on the benefits of grinding feed ingredients in terms of milling throughput, nutrient utilisation, growth performance, and economics (Amerah et al. 2007; Boroojeni et al. 2016; Lyu et al. 2020). Recommendations on the performance of monogastric animals and the optimal particle size for

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gastrointestinal development are contradictory (Amerah et al. 2007). Methods of measuring and expressing particle size are different; in order to describe particle size distribution. At present, dry sieving is the most widely used method for studying particle size in animal nutrition as it is a low-cost method (Lyu et al. 2020). Unlike dry sieving, the use of water in the sieving procedure (wet sieving) is considered more accurate because it avoids particle clogging and is similar to the hydration process in the intestine (Lyu et al. 2020).

Studies have shown the importance of the water-holding capacity (WHC) and swelling capacity (SC) of feeds for an effective digestion in animal feeding (Serena and Bach Knudsen 2007; Jiménez-Moreno et al. 2011; Arroyo et al. 2012; Priester et al. 2020). Hydration capacity (WHC and SC) of feed seems to influence the transit time, feed intake, the feeling of satiety, and organ development (such as birds' crop) (Lindberg 2014; Brachet et al. 2015; Priester et al. 2020). Although this parameter is sometimes mentioned to explain some results, it is rarely used in feed formulation as a predictive parameter in terms of feed passage, feed intake, and organ development (Brachet et al. 2015). The WHC could be a good tool to improve food characterisation models and can be used for fibre characterisation (Serena et al. 2008; Gous 2014; Slama et al. 2019). Priester et al. (2020) indicated that a high fibre diet in sows with a greater SC is beneficial for the development of the gastrointestinal tract and results in a higher feed intake during lactation overall. This would require the availability of databases providing this parameter for the more common raw materials used in animal nutrition.

Viscosity is a physicochemical property associated with dietary fibre, particularly soluble dietary fibre (Dikeman and Fahey 2006; Chen et al. 2020) which could led to decrease in nutrient absorption and digestibility in poultry (Bedford and Classen 1992; Singh and Kim 2021) and pigs (Serena et al. 2008; Gao et al. 2015). Moreover, the increased viscosity can hold water in the digesta and produce very wet excreta in poultry (Choct and Annison 1990; Bach Knudsen 1997; Cengiz et al. 2017). Unfortunately, no standardisation as regards measurement of viscosity exists in nutritional science, making inferences and comparisons among studies difficult (Dikeman and Fahey 2006; Rodehutscord et al. 2016).

To the best of our knowledge, data in literature regarding sedimentation rate as a physico-chemical parameter for cereals are very rare. Nevertheless, this parameter could be of particular interest in the case of using liquid feed for pigs. Liquid feeding involves the use of a diet prepared either from a mixture of liquid food industry by-products and conventional dry materials, or from dry raw materials mixed with water (Brooks et al. 2003). Liquid feeding may alter the physico-chemical properties of the diet, which is an important factor for homogeneous transport of liquid diets through feeding pipes.

Thus, this study aimed to obtain more extensive quantitative ideas concerning different physico-chemical properties including particle size distribution, hydration property, extract viscosity, and sedimentation of wheat, hybrid rye, and barley. In the present study, it was hypothesised that differences among physico-chemical properties of the selected grains could contribute to get closer for taking decision about the amount and form of the grain to be used in the monogastric nutrition as it may affect its health and performance.

Materials and methods

Samples and grinding

Three different cereal grains were investigated, including three different genotypes of wheat, hybrid rye, and barley. For wheat, a sample from Höveler Spezialfutterwerke GmbH & Co KG, Dormagen, Germany and two varieties 'Julius' and 'Talent' from KWS Lochow GmbH, Bergen, Germany were used. One sample of hybrid rye (Mühlenbetrieb Sendker GmbH, Kamen, Germany) and two varieties, called 'Binntto' and 'Eterno' (KWS Lochow GmbH) were employed. The three varieties of barley, 'Higgins', 'Meridian', and 'Wintmalt' were supplied by KWS Lochow GmbH (Table 1).

The grain samples obtained from the suppliers were ground in the institute's hammer mill (Rasant-Super®, Ley, Sulingen, Germany) at 2920 rpm ($n = 3$ for each variety of cereal). Sieve sizes of 1, 3 and 6 mm diameter produced grinding of varying fineness, which was then sampled with the aid of a sample divider (Tyler sample divider type 1, Haver & Boecker OHG, Oelde, Germany) for analysis. A rotor mill/ultra-centrifugal mill (Retsch ZM 200 mill, Retsch GmbH, Haan, Germany) with a 0.5 mm diameter sieve was used for the finest comminution of the samples (cereal grains).

Measurements

Dry matter content

To determine the DM content, about 50 g of fresh sample material was weighed and then heated at

Table 1. Characterisation of the grain samples used with regard to the origin and name of the grain samples.

Cereal	Origin (Germany)	Name of the grain variety
Wheat	Höveler Spezialfutterwerke GmbH & Co KG, Dormagen	128–139791
	KWS Lochow GmbH, Bergen	Julius
	KWS Lochow GmbH, Bergen	Talent
Rye	Mühlenbetrieb Sendker GmbH, Kamen	899217
	KWS Lochow GmbH, Bergen	Binntto
	KWS Lochow GmbH, Bergen	Eterno
Barley	KWS Lochow GmbH, Bergen	Higgins
	KWS Lochow GmbH, Bergen	Meridian
	KWS Lochow GmbH, Bergen	Wintmalt

The average dry matter (DM) contents of wheat, hybrid rye, and barley were 89.4% ± 0.78, 88.3% ± 0.40 and 88.0% ± 0.34, respectively.

103 °C in a drying oven (FD 115, Binder, Memmert GmbH & Co. KG, Schwabach, Germany) for at least 4 h until the weight was constant. Thereafter, the dry samples were cooled down in desiccators. The method and the calculation were based on the gravimetric method 3.1 in VDLUFA (2012).

Dry sieve analysis

For dry sieve analysis, about 50 g of ground material was placed on a sieve tower consisting of eight analysis sieves (mesh sizes: 3.15, 2.0, 1.4, 1.0, 0.8, 0.56, 0.4, and 0.2 mm, respectively) in accordance with the Association of German Agricultural Analyses and Research Department (VDLUFA 2012) described by (Wolf et al. 2010). The sieve stack was then placed in the sieve shaker (Retsch GmbH) and run for the specified time (10–15 min). Thereafter, each sieve was weighed with the sieve agitator(s) to obtain the weight of the sample for each sieve. Subsequently, the mass of each sieve fraction could be determined by differential calculation (mass sieve fraction = mass sieve with sample − mass sieve without sample).

Wet sieve analysis

The wet sieve analysis was carried out as described by Borgelt (2015) using the same sieves as for the dry sieve analysis. The sieves were dried at 103 °C until constant weight was achieved, and then cooled to room temperature in a desiccator. The individual sieves were then weighed, thus completing the preparation of the sieve tower. For sample preparation, about 50 g of the sample to be analysed was filled into a beaker. Afterwards, 800 mL of distilled water was added and the sample was mixed vigorously for 10 s. After 1 h of soaking, stirring was repeated. The suspension was then added to the top sieve (largest mesh size) of the already prepared sieve tower. A further 10 L of distilled water was used to rinse the sieve tower. The wet sieve tower including the sample material was placed in the drying oven (model 600, Memmert GmbH & Co. KG) overnight. On the following day, the sieves were placed in the desiccator to cool down and could then be weighed again. The dry fractions on the individual sieves were calculated as a percentage of the total amount of weighed dry matter. The percentage of particles $<200\,\mu m$ included those particles that were dissolved out or washed out. Accordingly, this fine fraction could be calculated by subtracting the total mass of DM weighed and the sum of the DM masses on the individual sieves. The wet sieve analysis tests were repeated as previously mentioned but with a soaking phase of 24 h instead of 1 h.

Geometric mean diameter (GMD)

The comparison between results of different sieve analyses was done by calculating the GMD with only one value. The formula for calculating the GMD was modified by Wolf et al. (2012). The GMD can be used for both dry and wet sieve analysis and is expressed in the unit μm.

Hydration property

The hydration capacities were evaluated measuring the water-holding capacity (WHC) and the swelling capacity (SC). Methods to measure WHC and SC have been previously described by Giger-Reverdin (2000). Briefly, to measure WHC, 2 g of raw material was mixed with 10 mL of distilled water. After 24 h at room temperature, the mixture was centrifuged (966 × g for 10 min at 20 °C, Heraeus Biofuge Stratos, Kendro Laboratory Products GmbH, Osterode, Germany). The supernatant was removed before weighing the hydrated material. WHC was expressed as g H_2O/g DM. To measure SC, 25 mL of distilled water was added to 2 g of raw material in a burette. The volume of the sample was measured after 24 h, adding the water as mL H_2O/g DM. WHC and SC were measured in triplicate on the ground cereals (Serena and Bach Knudsen 2007; Frikha et al. 2011).

Table 2. The particle size distribution (in % of fresh weight) and geometric mean diameter (GMD, in μm) after dry sieve analysis.

	Sieve size (mm)											
	1				3				6			
Parameters	Wheat	Hybrid rye	Barley	*P*-value	Wheat	Hybrid rye	Barley	*P*-value	Wheat	Hybrid rye	Barley	*P*-value
>1.0 mm	4.63^{b}	9.13^{a}	7.04^{ab}	.033	19.1^{c}	27.3^{a}	24.4^{b}	.001	19.3^{b}	26.8^{a}	19.1^{b}	.009
<0.2 mm	30.9^{a}	30.9^{a}	22.0^{b}	.002	18.0^{a}	15.5^{a}	10.2^{b}	.005	13.1^{a}	8.09^{b}	5.09^{b}	.009
GMD	310^{b}	341^{ab}	383^{a}	.020	521^{b}	616^{ab}	676^{a}	.030	740^{b}	920^{ab}	1149^{a}	.024

[a,b,c]Indicates significant differences within each row of each sieve hole ($p < .05$) between the different grains.

Extract viscosity

Extract viscosity was determined based on the method described by Dusel et al. (1997). About 5 g fresh ground grain was added to 20 mL tap water and then shaken for 5 s on a vortex mixer (Heidolph Reax 2000, Fa. KaliChemie Pharma GmbH, Hannover, Germany). After a standing time of 30 min at 38 °C (incubator model 500, Memmert GmbH & Co. KG), the samples were processed again using a vortex mixer and then centrifuged for 5 min at a force of 10,000 g (Heraeus Biofuge Stratos, Kendro Laboratory Products GmbH). After centrifugation, the viscosity was determined using Model DV-II + Viscometer (Brookfield Engineering Laboratories, Inc., Stoughton, MA, USA). For this purpose, 600 μL were removed from the supernatant fluid in the centrifuge tubes and transferred to the measuring unit of the viscometer set at 26 °C. The measuring unit contained an S40 spindle that rotated at 10 rpm. After 1 min, the specified value was recorded.

Sedimentation

For characterising the sedimentation rate, 100 g ground grain (fresh) and 300 mL water were added to a 600 mL beaker and mixed by a magnetic stirrer (Ikamag® RCT, Fa. IKA® Labortechnik, IKA-Werke GmbH & Co. KG, Staufen, Germany). After 5 min, the sample mixture was transferred into a 500 mL measuring cylinder. The stirring vessel was then rinsed with 100 mL of the tap water. A further mixing procedure (stirring) followed by means of a glass rod for 30 s, after which the sample was left at room temperature. After 0.5, 1, 2, 3, 4, 5, 6 and 12 h, the volume of the 'sediment layer' was read off. This 'sediment layer' was defined as the layer consisting of particulate matter that settled at the bottom of the measuring cylinder. This layer had to be distinguished from the 'flotation layer', which, like the sediment layer, consisted of solid particles, which, however, rose upwards in contrast to the former. Finally, the layer between the sediment and flotation layers was referred to as the 'middle layer'. This layer consisted of a macroscopically largely particle-free, but turbid liquid. In order to take into account small deviations in the weight of the material, a corrected sediment value was calculated, which was adjusted by the weight factor. The calculation was performed for each cereal variety and each time stage as follows.

$$\text{Corrected sediment rate (mL/g fresh)} \\ = \text{sediment layer (mL)/weight (g fresh)}$$

Statistical evaluation

The statistical analysis was performed with the Statistical Analysis System for Windows, SAS® 9.4 using the Enterprise Guide Client Version 7.1 (SAS Institute Inc., Cary, NC, USA). The assumption of normal distribution of quantitative characteristics was checked by visual observation of the qq-plots of the model residuals and the Shapiro-Wilks test. Depending on the distribution analysis and the scaling of the data, both parametric and non-parametric methods were applied. Significant differences between the groups were tested using the repeated measures ANOVA (post-hoc Fisher's Least Significant Difference). The significance level alpha was set at 5.00% ($p < .05$).

Results

Dry sieve analysis

The results of the dry sieve analysis of the cereals ground by the hammer mill are shown in Table 2. Significant differences ($p = .033$) were observed for cumulative mean particle size distribution at >1.0 mm between wheat and hybrid rye ground with 1 mm sieve diameter (4.63% and 9.13%, respectively). Cumulative mean particle size distribution at >1.0 mm for barley (7.04%) ground with 1 mm mesh sieve was similar for the other cereals. Ground wheat and hybrid rye with 1 mm mesh sieve showed identical cumulative mean particle size distribution (30.9%) at <0.2 mm. However, ground barley with 1 mm mesh sieve had the lowest ($p = .002$) cumulative mean particle size distribution (22.0%) at <0.2 mm compared to

Table 3. Particle size distribution (> 1.0 mm and < 0.2 mm, in % of dry matter weight) and geometric mean diameter (GMD, in μm) for cereals after wet sieve analysis (soaking time: 1 h and 24 h).

		Sieve size (mm)							
		3				6			
Soaking time	Parameters	Wheat	Hybrid rye	Barley	*P*-value	Wheat	Hybrid rye	Barley	*P*-value
1 h	>1.0 mm	13.9[a]	14.5[a]	15.1[a]	.721	9.59[ab]	11.5[a]	11.7[a]	.085
	<0.2 mm	31.2[b]	35.7[a]	20.9[c]	<.001	24.5[a]	26.1[a]	14.0[b]	.004
	GMD	524[b]	487[b]	713[a]	.005	764[b]	730[b]	1233[a]	.007
24 h	>1.0 mm	10.0[a]	10.2[a]	13.3[a]	.209	8.83[a]	8.35[a]	8.50[a]	.948
	<0.2 mm	53.7[a]	62.0[a]	29.6[b]	.002	45.4[a]	54.8[a]	21.8[b]	.002
	GMD	305[b]	250[b]	586[a]	.002	431[b]	336[b]	1053[a]	.003

[a,b,c]Indicates significant differences within each row of each sieve hole ($p < .05$) between the different grains.

other cereals. Ground barley with 1 mm mesh sieve had the higher GMD ($p = .020$) compared to ground wheat (383 and 310 μm, respectively).

When using a 3 mm mesh sieve, hybrid rye had a significantly higher mean particle size distribution of >1.0 mm (27.3%) in comparison to ground wheat and barley (19.1 and 24.4%, respectively), while barley showed at a 3 mm mesh sieve diameter a significantly lower mean particle size distribution of <0.2 mm (10.2%) in comparison to ground wheat and barley (18.1% and 15.5%, respectively). The GMD diameter for wheat ground using a 3 mm mesh sieve was significantly lower (521 μm) compared to ground barley (676 μm).

When using a 6 mm mesh sieve, hybrid rye had a significantly higher mean particle size distribution of >1.0 mm (26.8%) than for ground wheat and barley (19.3 and 19.1%, respectively). Wheat showed with a 6 mm mesh sieve significantly the highest mean particle size distribution of <0.2 mm (13.1%) in comparison to ground hybrid rye and barley (8.09 and 5.09%, respectively). The GMD diameter differed significantly ($p = .024$) among the cereals (740, 920, and 1149 μm for wheat, hybrid rye, and barley, respectively).

Wet sieve analysis

Cumulative mean particle size distribution and GMD for the different cereals after wet sieve analysis with soaking time 1 h and 24 h are presented in Table 3. The percentage of particles of >1.0 mm (soaking 1 h) were similar among the ground cereals with a 3 mm mesh sieve ($p = .721$). Significant differences were found at 3 mm between all ground cereals soaked for 1 h at <0.2 mm (20.9%, 31.2%, and 35.7% for barley, wheat, and hybrid rye, respectively).

The GMD fractions of ground barley (713 μm) differed ($p = .005$) compared to ground wheat and barley (524 and 487 μm, respectively) at 3 mm (soaking 1 h). After soaking time (24 h), the percentage of particles of >1.0 mm showed the same trend ($p = .209$) as for soaking for 1 h. Also, after 24 h soaking time ground barley at 3 mm still showed the lowest ($p = .002$) percentage of particles <0.2 mm (29.6%) than for other ground cereals, while the GMD for ground barley at 3 mm after soaking time (24 h) had a higher ($p = .002$) fraction (586 μm) in comparison to ground wheat and barley (305 μm and 250 μm, respectively).

At 6 mm sieve diameter and after soaking for 1 h, all ground cereals showed similar particle size distributions ($p = .085$), while at <0.2 mm and after 1 h soaking time, ground barley at 6 mm had the lowest ($p = .004$) particle size in comparison to wheat and hybrid rye (14.0% vs. 24.5% and 26.1%, respectively). The GMD fraction after 1 h soaking time of ground barley when using a 6 mm sieve diameter showed the highest ($p = .007$) particle size distribution in comparison to wheat and hybrid rye (1233, 764, and 730 μm for barley, wheat, and hybrid rye, respectively). Finally, after 24 h soaking time, ground cereals at 6 mm sieve diameter did not differ ($p = .948$), with a mean particle size distribution of >1.0 mm. However, after 24 h soaking time, ground wheat and hybrid rye at 6 mm sieve diameter had significantly the higher mean particle size distribution of <0.2 mm (54.8 and 45.4%, respectively) compared to ground barley (21.8%). The GMD fraction of ground barley at 6 mm diameter was the highest ($p = .003$) after 24 h soaking time (1053 μm vs. 431 μm and 337 μm for barley, wheat, and hybrid rye, respectively).

Water holding capacity and swelling capacity

Water holding capacity and swelling capacity for the individual cereal varieties after an incubation period of 24 h are presented in Table 4. The type of cereals as well as the grinding had a significant influence on WHC and SC. Ground wheat at 1 mm mesh sieve had the lowest WHC (1.89 g H_2O/g DM; $p = .001$) compared to hybrid rye and barley (2.64 and 2.56 g H_2O/g DM, respectively). Ground wheat at 1 mm mesh sieve had the lowest SC (1.33 mL H_2O/g DM; $p = .021$) compared

Table 4. Water holding capacity (g H2O/g dry matter) and swelling capacity (mL H2O/g dry matter) of different cereals.

	Sieve size (mm)											
	1				3				6			
Parameters	Wheat	Hybrid rye	Barley	*P*-value	Wheat	Hybrid rye	Barley	*P*-value	Wheat	Hybrid rye	Barley	*P*-value
Water holding capacity	1.89^b	2.65^a	2.56^a	.001	1.82^b	2.67^a	2.74^a	.015	2.02^b	2.71^a	2.60^a	<.001
Swelling capacity	1.33^b	1.60^a	1.51^a	.021	1.40^b	1.67^a	1.56^{ab}	.027	1.48^b	1.60^a	1.49^b	.026

^{a,b} Indicates significant differences within each row of each sieve hole ($p < .05$) between the different grains.

to hybrid rye and barley (1.60 and 1.51 mL H_2O/g DM, respectively). The WHC for ground wheat at 3 mm was the lowest (p-value = .015) in comparison to other cereals (1.82 vs. 2.67 and 2.74 g H_2O/g DM for wheat, hybrid rye, and barley, respectively). At 3 mm mesh sieve, ground wheat had significantly lower SC (1.40 mL H_2O/g DM) compared to hybrid rye (1.67 mL H_2O/g DM). However, ground barley at 3 mm had similar SC as for ground wheat and hybrid rye. Finally, regarding the 6 mm mesh sieve, ground wheat had the lowest WHC (2.02 g H_2O/g DM; $p < .001$) compared to ground hybrid rye and barley (2.71 and 2.60 g H_2O/g DM, respectively). While ground hybrid rye had the highest SC (1.60 mL H_2O/g DM; $p = .026$), ground wheat or barley had the lowest SC (1.48 and 1.49 mL H_2O/g DM, respectively).

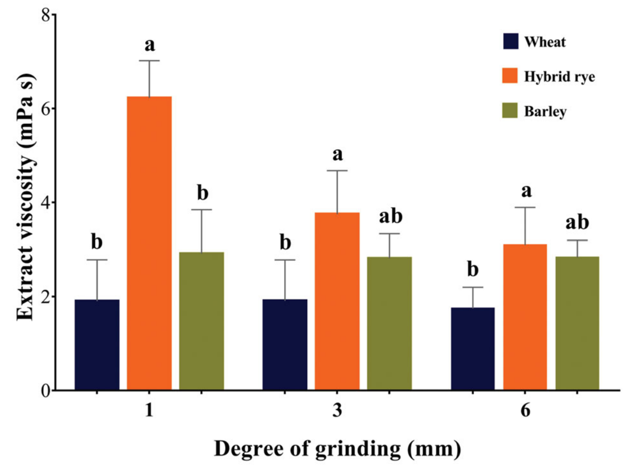

Figure 1. Extract viscosities of different cereal samples as a function of the degree of grinding (n = 3 each). [a, b] Indicates significant differences of each sieve hole ($p < 0.05$) between the different grains.

Extract viscosity

Extract viscosities of different cereal samples of different degrees of grinding ($n = 3$ each) are presented in Figure 1. Ground hybrid rye at 1 mm had significantly the highest extract viscosity (6.22 mPa s) compared to ground wheat and barley (1.90 and 2.91 mPa s, respectively). Also, ground hybrid rye with the 3 and 6 mm mesh sieves showed significantly higher extract viscosity compared to ground wheat but not to ground barley.

Sedimentation rate

Throughout the sedimentation time (from 2 h to 12 h), it was noted that ground wheat with a 1 mm mesh sieve had significantly ($p < .001$) the lowest corrected sediment rate compared to other ground cereals (Figure 2). After only 1 h, significant differences ($p < .001$) were found in the corrected sediment rate between all three ground cereals with a 3 mm mesh sieve, whereas ground barley had the highest volume (range: 3.05–3.08 mL/g) and ground wheat the lowest volume (range: 2.24–2.53 mL/g). Similarly, and in the same trend as previously mentioned, after 2 h, significant differences were found in the corrected sediment rate between all three ground cereals when using a 6 mm mesh sieve, whereas ground barley had the highest volume (range: 3.11–3.12 mL/g) and ground wheat (range: 2.30–2.41 mL/g) the lowest volume.

Discussion

The particle size parameters, WHC, SC, and extract viscosity, strongly affect the characteristics of feedstuffs and the practicability of feeding for monogastric animals (Zhao et al. 2019; McGhee and Stein 2020; Wilke et al. 2021). Therefore, in the present study, barley, rye, and wheat, commonly used in diets for monogastric animals, were tested regarding these parameters.

Particle size

Determining the mean particle size of feedstuffs that are commonly used in diets fed to pigs is not a well-established practice in feed mills. However, energy and nutrient digestibility may be increased as the particle size of feedstuffs decreases (Wondra et al. 1995; Rojas and Stein 2015, 2017). Therefore, it is important to determine the optimal particle size of feed ingredients to maximise energy and nutrient digestibility. Kiarie and Mills (2019) pointed out that one of the

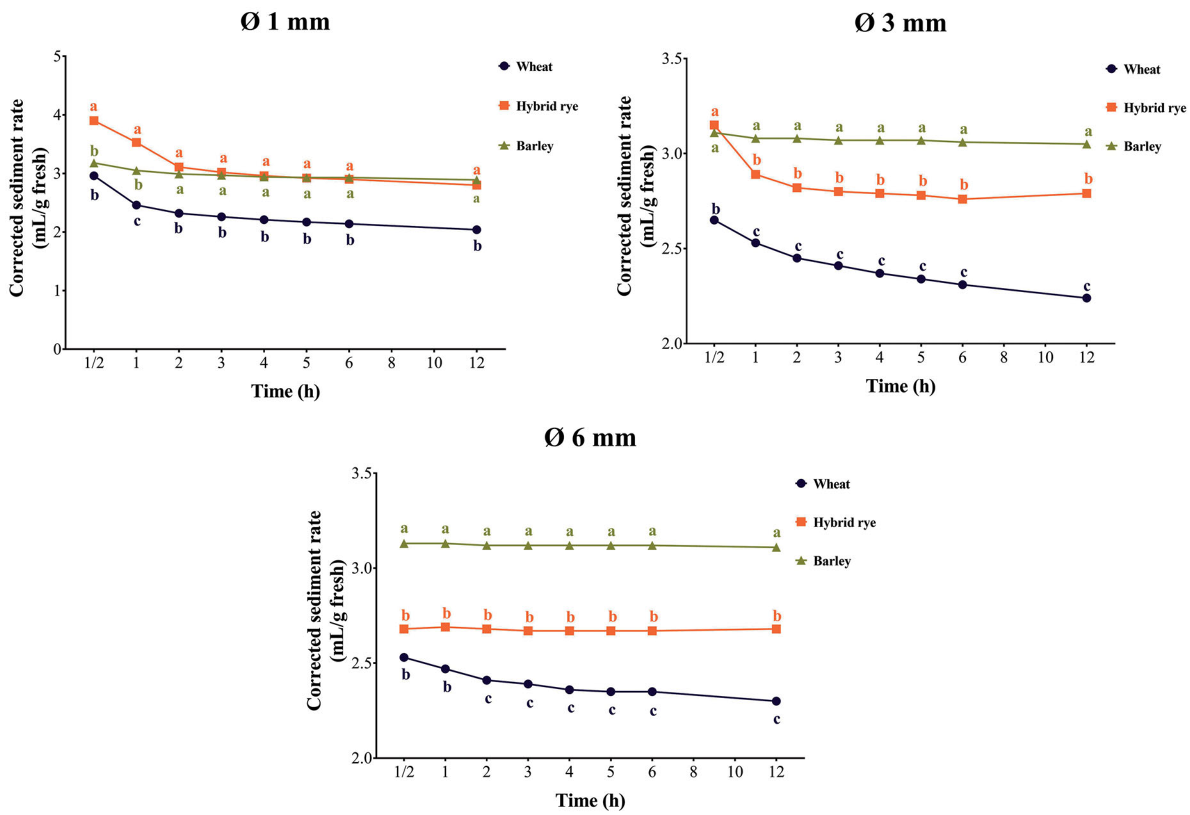

Figure 2. Corrected sediment rate (mL/g fresh) of ground cereals in water using different periods of time (h). [a, b, c] Indicates significant differences of each sieve hole for each time ($p < 0.05$) between the different grains.

most important factors that determines the use of monogastric animal feed is particle size distribution.

Physical feed form is considered to have a very significant impact on broiler growth and feed intake (Dozier et al. 2010). Years ago, however, it is thought that a large particle size aided by some structural components is beneficial to gizzard functions and gut development (Hetland et al. 2002; Svihus et al. 2004; Choct 2009). The importance of the physical structure of the diet as a means to improve feed efficiency and live performance has become increasingly recognised, and coarser feed structure has exhibited a positive influence on nutrient digestibility and animal live performance (Amerah et al. 2008; Abd El-Wahab et al. 2020).

The presence of a large number of fine particles in pig feed leads to a higher incidence of gastric ulcers and other negative changes in the gastric mucosa, as evidenced by keratinisation and erosion of the mucosa (Healy et al. 1994; Wondra et al. 1995; Celi et al. 2017; Vukmirović et al. 2017). Nevertheless, deleterious effects of finer particle size in pigs is dependent on grain type (Cappai et al. 2013). For example, macroscopic keratosis scores were greater for pigs fed 0.30 vs. 0.90 mm corn and hard sorghum, but lower for pigs fed 0.30 vs. 0.90 mm soft sorghum (Healy et al. 1994). The grinding intensity of the diet appears to be within the list of risk factors for occurrence of gastric ulceration in pigs (Wondra et al. 1995; Celi et al. 2017). To date, the extent to which the prevalence of gastric lesions increases with particle size smaller than 700 µm appears to be unstated (Cappai et al. 2013). Thus, the recommendations for optimum particle size are sometimes contradictory, as the results from feeding trials are confounded by a number of factors including feed physical form, particle size distribution, grain type and grinding method (Amerah et al. 2007; Celi et al. 2017; Vukmirović et al. 2017).

In poultry diets, for example, the lack of structural component has been associated with dilated proventriculus and a non-functional gizzard consequently compromising feed utilisation and intestinal health (Mateos et al. 2012; Svihus 2014). It has been reported that the volume of the gizzard may increase substantially when structural components such as whole or coarsely ground cereals are added to the diet (Amerah et al. 2007; Röhe et al. 2014; Abd El-Wahab et al. 2020), sometimes increasing to more than double the original size (Svihus 2014). However, inhomogeneous feed mixtures with high levels of coarse particles promote selective intake of coarser feed components, resulting in an imbalanced nutrient supply (Lieboldt et al. 2018).

Overall, the data in the current study revealed that hybrid rye usually showed a higher particle size distribution (>1 mm) in each ground intensity than other cereals, while wheat and barley showed a comparable particle size distribution (>1 mm) in each grinding intensity. Moreover, using wet sieve analysis in the present study did not show any differences among the cereals ground either at 3 or 6 mm in the particle size distribution (>1 mm) nor in particle size distribution of <0.2 mm.

WHC and SC

The data show that WHC and SC varied greatly between the different raw materials. These two parameters are also greatly influenced by the particle size of the raw material. The WHC values (g H_2O/g DM) for ground wheat (1 mm = 0.69; 3 mm = 0.79; 5 mm = 1.23) and barley (1 mm = 0.99; 3 mm = 1.33; 5 mm = 1.52) mentioned by Brachet et al. (2015) were slightly lower than in our study (Table 4). In the current study, ground hybrid rye has a higher hydration capacity at different mesh sieve sizes, and mainly a high SC compared to ground wheat. However, in the present study, the SC values for wheat and barley ground using a 3 and 6 mm mesh sieve were comparable. Brachet et al. (2015) obtained similar trends for SC (0.86 and 0.94 g H_2O/g DM for ground wheat and barley at 3 mm, respectively) as in the present study.

Technological processes have a large influence on hydration capacities of raw materials, due to changes in the surface and the accessibility by water (Jacobs et al. 2015). Nevertheless, one effect of grinding on the WHC and SC was shown in our own study; the very fine grinding did not tend to decrease the WHC and SC for the cereals. However, Raghavendra et al. (2006) observed a decrease in hydration capacities (WHC and SC) with a reduction in particle size from 1127 to 550 µm. As a general rule, grinding increases the contact surface area, breaks the endosperm of the whole seed, and improves the accessibility of water to the surface capillaries (Frikha et al. 2011); however, this was not confirmed in our study. It could be that reduction in particle size from 6 mm to 1 mm was insufficient to exert this effect.

Brachet et al. (2015) found that the correlation between WHC and SC values was weak among cereals (i.e. a high WHC did not necessarily mean a high SC). Both are important to characterise the hydration capacity of a raw material. They refer to different functional traits; for a weight of water absorbed (WHC) or potential volume occupancy in the digestive tract after hydration (SC). For example, WHC seems more relevant to deal with issues such as litter quality in poultry (Ouhida et al. 2000; Cengiz et al. 2017), while SC seems more suited to solve the issues of crop expansion in waterfowl (Arroyo et al. 2015).

The non-starch polysaccharide (NSP) cell wall in plants consists of a group of molecules with varying degrees of water solubility, size, and structure, all of which can affect the rheological properties of gastrointestinal contents, digesta flow, and the digestion and absorption process (Bach Knudsen and Jørgensen 2001). According to Rodehutscord et al. (2016), the total NSP content was 98.2, 139, and 172 g/kg DM for wheat, rye, and barley, respectively, whereas the crude fibre content was 21.3, 17.9, and 42.2 g/kg DM for wheat, rye, and barley, respectively (Rodehutscord et al. 2016). The WHC and SC have been shown to be linked to fibre content (Bach Knudsen and Jørgensen 2001; Singh and Kim 2021). In some research studies, the amount of soluble non-cellulosic polysaccharides and WHC in plant material and agro-industry co-products was found to be highly correlated (Ngoc et al. 2012). This could be because soluble non-cellulosic polysaccharides in feed ingredients cause greater gaps inside the cell matrix, which can hold excess water (Serena and Bach Knudsen 2007).

Viscosity

The results in the current study showed that ground hybrid rye at 1 mm had the highest viscosity (6.22 mPa s) compared to ground wheat and barley (1.90 and 2.91 mPa s, respectively), while ground hybrid rye at 3 and 6 mm mesh sieves showed higher extract viscosity compared to ground wheat but not to ground barley. Despite an identical sieve diameter size at grinding (1 mm) in our study, the extract viscosity (6.22 mPa s) measured for ground hybrid rye was markedly lower than the measured mean values for 22 samples of rye (20 mPa s) mentioned by Rodehutscord et al. (2016). According to Rodehutscord et al. (2016), the extract viscosity for wheat ($n = 29$) and barley ($n = 21$) were 1.94 and 1.12 mPa s, respectively. A variation in apparent extract viscosity between wheat genotypes was reported in the literature (Dusel et al. 1997; Grosjean et al. 1999; 1999; Rodehutscord et al. 2016).

In the context of dietary fibre, viscosity refers to the ability of some polysaccharides to thicken or form gels when mixed with fluids due to physical entanglements between polysaccharide elements within the fluid or solution (Guillon and Champ 2000; Dikeman and Fahey 2006; Chen et al. 2020). Polysaccharides that form viscous solutions, such as gums and pectins, form thickened solutions dependent on their unique chemical composition (Schneeman 2001). The viscosity was positively correlated ($p \leq .05$) with the concentrations of some NSP fractions (soluble arabinose, $r = 0.58$; soluble xylose, $r = 0.62$; total arabinose, $r = 0.82$; total xylose, $r = 0.72$; galactose, $r = 0.54$; glucose, $r = 0.45$; cellulose, $r = 0.46$) in rye (Rodehutscord et al. 2016). It was also positively correlated ($p \leq .05$) with the total galactose concentration ($r = 0.49$) in wheat (Rodehutscord et al. 2016). Additionally, positive correlations between extract viscosity and soluble pentosan concentrations in wheat were also determined by Dusel et al. (1997). The high level of extract viscosity especially in rye may also be related to certain protein fractions (Hansen et al. 2004), because Weipert (1997) found rye to have a high content of water-extractable proteins compared to other cereals. Overall, hybrid rye, in general, is characterised by high extract viscosity (6.22 mPa s at 1 mm), which decreased with coarser grinding (3.75 and 3.10 mPa s at 3 and 6 mm, respectively).

Sedimentation

In the current study, significant differences in the sedimentation rate among the different cereal meals with the same grinding were found. The ground hybrid rye showed a lot of sediment (= little supernatant), about 3.53 mL/g fresh during the 1 mm grinding especially for the first hour. However, after one hour (2 h–12 h of water soaking) at 1 mm grinding, the sedimentation rates for ground hybrid rye and barley were comparable (range: 2.80–3.11 mL/g fresh). Furthermore, in this present study, at other subsequent grinding intensities (3 and 6 mm), the ground barley had the highest sediment rate (from 1 h till 12 h), followed by ground hybrid rye and finally, wheat meal (little sediment, high percentage of aqueous supernatant). In general, the results in the present study showed that wheat had always the lowest sedimentation rate regardless of grinding intensity. Increasing the grinding intensity (3 mm or 6 mm) led to the highest sedimentation rate for barley.

Conclusions

Wheat, barley, and rye are components primarily used in feeding, especially in monogastric animals. Irrespective of their chemical composition, the physicochemical characteristics, variously influenced by feed processing, do affect the feed itself and thus have an effect on the nutrient digestibility, performance, and hence the health of the animal. The results showed that even with identical grinding procedures, identical particle size distributions cannot be assumed. Wheat tended to have a lower particle size structure than rye and especially barley. Therefore, the ideal intensity of grinding also depends on the cereal itself. Regarding suitability of transport and unmixing of liquid feedstuffs, the extract viscosity is of particular interest. It has been shown that the latter is determined both by grinding and the cereal itself. Regarding presented findings, rye can be used specifically for the purpose of increasing viscosity. This results in an optimal situation, positively influencing the technical properties of feed (reducing risks of demixing), specifically in liquid feeding systems for pigs.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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