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Classification of commonly used feed ingredients based on flow properties**

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A b s t r a c t. The objective of this report was to classify ingredients based on their flowability. Twenty-six different feed ingredients (52 samples) were used including cereal grains, cereal by-products, oilseeds, oilseed meals, and animal-origin products. As an indication of flowability, the angle of repose was determined using a funnel test. In general, high protein oilseed meals had the lowest angle of repose, and therefore they had the highest flowability with the exception of cottonseed meal. Corn gluten feed and wheat middlings had the highest angle of repose values (39 and 34°, respectively), and therefore they had the lowest flowability. Ingredients with a range of angle of repose values between 22 and 25°, between 27 and 30°, and more than 30°, were categorized as having an easy flow, a moderate flow, and cohesive, respectively. The greater the protein content, the smaller the compressibility value (r = –0.38) and the lower the angle of repose (r = –0.42). An increase in the ether extract content of the ingredients resulted in a subsequent increase in angle of repose (r = 0.31) and therefore a decrease in flowability ($p<0.05$). The angle of repose was positively correlated with compressibility and the Hausner ratio. In conclusion, oilseed meals were classified as "easy flow", most by-products as "moderate flow", and cereal grains as "cohesive".

K e y w o r d s: angle of repose, compressibility, feed, flowability, Hausner ratio

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INTRODUCTION

Global compound feed production was estimated to be approximately one billion tonnes in 2017 (Alltech, 2017). Compound feed is produced for the most part from a wide range of ingredients including cereal grains, cereal by-products, oilseeds, oilseed meals, and animal-origin products. Each of these different ingredients possesses different physical and chemical characteristics that may vary widely due to harvesting, storing, processing, and other related processes (Moss *et al*., 2021). Even though the nutrient composition of the feeds is closely monitored in the field, the physical characteristics of the ingredients have been neglected by the feed industry for a variety of reasons (including both economic and technical issues).

Water holding capacity, bulk density (*BD*), apparent density, solubility, swelling, and particle size are some of the most important indicative physical parameters for high-quality ingredient selection and feed production (Hao *et al*., 2016). As an example, the pellet quality of feeds is influenced by the physical characteristics of each ingredient used to produce the pellets, in addition to its chemical composition. (Thomas and Van der Poel, 1996). One such physical attribute is the geometric mean diameter of the feed. For instance, it has been reported that a 650 to 700 µm geometric mean diameter is found to be optimal for pellet quality in corn-soy diets (Dozier, 2001). The pelleting process increases the *BD* and flowability of feed (Briggs *et al*., 1999). Therefore, the physical parameters of the feed should be monitored closely to ensure that its quality is not compromised.

The flowability attribute is one of the most imperative physical peculiarities of feed ingredients and plays a role in its usability in the field. Feed ingredients are usually ground and mixed to form a final product, transported using various vehicles and stored in bins or silos, and finally they are moved through automated chain feeding systems. All of these stages can be affected by their flow characteristics (Matchett, 2006). For instance, feed segregation and caking are two flow property-related problems that can lead to significant economic losses to the feed industry (Tang *et al*., 2006). Some of the ingredients in compound feeds have been shown to be prone to caking, particularly when in transit, thereby resulting in detrimental effects on overall feed quality and flowability (Aguilera *et al*., 1995).

The angle of repose (*AR*) is defined as the maximum slope inclination of any comminuted material when it is barely stable, it affects the flowability of any granule, including feed (Al-Hashemi and Al-Amoudi, 2018). The chemical composition of various ingredients, such as the amount of moisture, fat, and protein can also have an impact on the flowability of feed (Bhadra *et al*., 2008). For instance, the flow of distillers dried grains with solubles (DDGS) can be problematic due to the caking and bridging that develop during the course of transportation and storage according to Ganesan *et al*. (2008). The chemical composition (*e.g.*, moisture and fat content) of DDGS was shown to affect its flowability (Ganesan *et al*., 2009; Johnston *et al*., 2009). In contrast, Pekel *et al*. (2020) reported that the nutrient composition of DDGS only had a limited influence over its flow characteristics.

Despite several past publications concerning the flow characteristics of some feed ingredients, up-to-date information about the flowability of widely used feed ingredients is lacking in a single report format. It was hypothesized that the flow characteristics of ingredients could be classified using physical and chemical properties. To that end, the current study was designed to explore the flowability characteristics of the commonly used feed ingredients in the field and to identify correlations between flowability and certain physical/chemical properties of the ingredients.

MATERIAL AND METHODS

Twenty-six different feed ingredients and a total of 52 samples were used including cereal grains, cereal by-products, oilseeds, oilseed meals, and animal-origin products. The samples were crumbled and moved across a 0.5 mm screen in a high-speed rotor mill (Retsch, ZM200, Haan, Germany) before analysis and physical measurement.

The ingredients were analysed in triplicate for aerated *BD*, tapped density (TD), mean bulk density (MBD), compressibility (*C*), and nutrient content. The calculation of aerated *BD* (kg m^{-3}) was carried out using the weight of the feed sample (15 g) divided by the volume of a measuring cylinder. After setting the initial volume at 100 ml followed by the treatment of a feed specimen (15 g) with a vortex shaker for approximately 2 minutes and manually hitting the cylinder prior to little volume change being observed, the *TD* (kg m^{-3}) was determined by dividing the mass of the feed specimen by its tapped volume. An average of the *BD* and *TD* was taken to determine the MBD (kg m^{-3}) of the samples. The Hausner ratio (HR) was estimated by dividing the *TD* by the *BD*. The compressibility (*C*) of the ingredients was obtained by employing Carr's equation (Carr, 1965) as follows:

$$C = 100\left(1 - \frac{BD}{TD}\right) . \quad (1)$$

The *AR* for each ingredient was measured using a funnel test in triplicate and used as a guide for the flow attribute. The *AR* value of each feed ingredient was determined by fixing the funnel tip height to 2 cm from the horizontal surface using a ring stand. The diameter of the funnel, the length of its elongation, and its entire span were 18, 21, and 29 cm, respectively. A pile of feed ingredient was released in such a way as to flow smoothly via the funnel onto a filter paper until the crest of the pile underneath just touches the lower tip of the funnel placed on a ring stand. After that, the boundary of the loose feed ingredients on the filter paper was drawn using a marker, then the stack was discarded. The diameter of the assembled accumulation was evaluated twice (perpendicular and parallel) and its mean was taken. This activity was performed in triplicate and the mean diameter (d) and the radius (r = d/2) were measured. Using the height (h) and radius of the funnel, *AR* was determined by calculating the arctangent between the height and radius of the stockpile (Aliyu *et al*., 2010) using the following equation:

$$AR = \arctan\left(\frac{h}{r}\right) . \quad (2)$$

The dry matter content of the ingredients was obtained by using a forced-air drying oven (FN 500; Nüve, Ankara, Turkey) at 105°C overnight. Feed samples were allowed to burn in a muffle furnace (Model MF 110/30, Protherm Furnaces, Ankara, Turkey) for 12 h to determine the crude ash content. A Soxhlet extraction procedure using petroleum-ether for 2 h and 15 min in a Soxtec device (Model Soxtherm 406, Gerhardt Laboratory Systems GmbH, Koenigswinter, Germany) was used to estimate the ether extract content of the ingredients. The level of nitrogen was determined using Kjeldahl digestion by employing a commercial analyser (Gerhardt Kjeldatherm KB, Bonn, Germany). The crude protein values were calculated by multiplying the nitrogen values by 6.25 (AOAC, 2006).

The data were analysed by simple linear regression utilizing PROC REG. In addition, the PROC CORR statements were used to perform a Pearson correlation (R) analysis (SAS, 2006).

RESULTS AND DISCUSSION

The analysed average nutrient composition and physical features of the samples are presented in Table 1. Since mechanical milling affects the morphology and hardness of powder particles (Fogagnolo *et al*., 2003), all samples in the current study were crumbled in order to go across a 0.5 mm screen to achieve a homogeneous particle-size distribution. Molenda *et al*. (2002) reported a 583 kg m^{-3} *BD* value for the sampled corn, this was higher than the 488 kg m^{-3} value determined in the current study. The *BD* value of 368 found for barley in the current report was very close to the 340 kg m^{-3} value reported by Hamdani *et al*. (2014). The *BD* values for ground wheat, wheat bran, oats, and wheat middlings in the present study were in the range reported by Stanley (1981). Kammel (2000) reported 400, 448, 320, and 672 kg m^{-3} *BD* values for ground samples of barley, corn, oats, and corn gluten meal, which were very similar to the *BD* values of 368, 488, 346, 662 reported for the same ingredients in the current study, respectively. The *BD* data were consistent with the *TD* and MBD values in the current study. Sunflower hulls had the lowest *BD* value and beet pulp had the lowest *TD* and MBD values, while corn gluten meal had the highest *BD* value and meat and bone meal had the highest *TD* and MBD values in the current study. Some of the ingredients with the highest BD,

Table 1. Average nutrient composition (%, as-is) and physical characteristics of samples

Ingredients	n	Dry matter	Crude ash	Ether extract	Crude protein	Compressibility (%)	Bulk density (kg m^{-3})	Tapped density (kg m^{-3})	Mean bulk density (kg m^{-3})	Angle of repose (°)	Hausner ratio
Cereal grains											
Barley, flaked	1	89.94	2.23	2.27	9.99	48.39	362.90	703.13	533.01	32.16	1.94
Barley	1	88.37	2.16	1.91	12.11	41.80	368.85	633.80	501.33	30.79	1.72
Corn	3	89.44	0.92	5.07	8.00	27.68	488.51	668.69	578.60	28.89	1.40
Corn (full-fat)	1	96.88	2.90	12.59	18.73	33.65	432.69	652.17	542.43	31.79	1.51
Oat	1	91.62	3.76	7.75	12.49	45.38	346.15	633.80	489.98	33.20	1.83
Wheat	2	88.53	1.45	2.18	11.61	29.15	514.30	726.00	620.15	30.20	1.41
Cereal by-products											
Corn bran	1	87.05	0.81	4.97	8.53	27.82	338.35	468.75	403.55	32.97	1.39
Corn gluten feed	1	91.54	4.64	17.05	18.95	24.44	500.00	661.76	580.88	38.71	1.32
Corn gluten meal	1	91.56	1.75	2.37	62.27	7.35	661.76	714.29	688.03	24.18	1.08
Corn DDGS[1]	2	88.31	5.04	7.54	30.68	24.76	483.93	644.04	563.98	28.19	1.33
Wheat DDGS	1	90.06	4.02	3.16	32.65	21.98	494.51	633.80	564.15	26.86	1.28
Wheat bran	3	90.04	4.54	3.06	16.13	29.49	370.96	523.80	447.38	27.35	1.43
Wheat middlings	1	91.43	3.21	4.44	16.21	31.45	362.90	529.41	446.16	34.48	1.46
Oilseeds											
Sunflower seed	1	94.89	3.17	44.92	15.70	39.78	483.87	803.57	643.72	27.66	1.66
Oilseed meals											
Cottonseed meal	4	88.84	5.74	2.15	35.12	43.67	342.08	596.12	469.10	30.88	1.82
Pumpkin seed meal	1	93.82	6.79	12.19	22.74	36.13	378.15	592.11	485.13	26.67	1.57
Safflower meal	1	92.45	3.86	0.20	20.65	28.57	494.51	692.31	593.41	21.96	1.40
Soybean meal	9	90.51	6.96	2.24	47.86	20.93	591.74	748.59	670.16	25.06	1.28
Sunflower meal	8	89.70	6.36	1.19	32.80	20.38	429.84	540.86	485.35	24.68	1.26
Sunflower meal (full-fat)	1	95.94	7.43	7.42	41.36	43.70	378.15	671.64	524.90	29.97	1.78
Other by-products											
Beet pulp	1	86.94	4.27	0.82	9.47	27.21	306.12	420.56	363.34	28.28	1.37
Cocoa hulls	1	92.44	8.08	4.47	18.20	27.18	436.89	600.00	518.45	29.92	1.37
Soybean hulls	1	90.80	4.92	1.50	10.33	26.47	441.18	600.00	520.59	22.07	1.36
Sunflower hulls	2	91.04	3.50	10.08	6.85	34.31	295.71	445.02	370.36	27.32	1.53
Animal products											
Meat and bone meal	1	93.83	33.19	17.48	41.59	41.38	517.24	882.35	699.80	27.47	1.71
Other plant products											
Alfalfa	2	90.95	10.37	1.40	16.74	24.97	409.23	545.47	477.35	29.76	1.33

[1]DDGS: distillers dried grains with solubles.

TD and MBD (corn gluten meal, corn gluten feed, and soybean meal) values also had relatively low compressibility values as expected. Barley (flaked), oats, full-fat sunflower meal, and cottonseed meal had the highest compressibility values in the current study. Surprisingly, although the meat and bone meal had very high *BD* (517), *TD* (882), and MBD (699) values, it had a relatively high compressibility value (41.4) in the current study. Among the studied physical attributes, compressibility had the highest coefficient of variation (CV) value, while the lowest CV value was observed for *AR* (Table 2).

In cases where feed flow is a priority, it might be possible to determine which ingredients are better suited to be included in a commercial diet by assessing the potential flowability of the ingredients. As a consequence, the ingredients in the current study were arranged in 3 categories according to Carr (1965): those which had *AR* values between 22 and 25 are classified as "easy flow", those having *AR* values between 26 and 29 are classified as "moderate flow", and those possessing *AR* values higher than 30 are considered to be "cohesive" (Table 3). While giving flow characteristics based on the *AR* classification, the corresponding compressibility and HR values of the samples also corresponded to those found by Carr (1965) and Hausner (1967), respectively. The main flowability categorizations were made according to the *AR* ranking from the lowest to the highest value. As expected, the corresponding HR and compressibility values did not appear in the same order since correlations between *AR*, HR, and compressibility were moderate. Therefore, flowability classification based on HR and compressibility was accomplished by using the mean values for those parameters in the same samples and under the same classification according to their *AR* values. Whether an ingredient should be categorized in terms of excellent or very poor flowability depended on the interpretation method (compressibility, *AR*, and HR) used in the current study. The categorization of flow using HR garnered the poorest type of flow degree for the various ingredients studied. On the contrary, categorization by *AR* resulted in a better degree of flowability for the same ingredients used in the current study. Any powder with a compressibility value below 15% is considered to have a favourable flowability and values above 25% indicate poor flowability (Lachman, 1986). Moreover, powders with a HR value of 1.25 or larger indicate poor flowability. Therefore, among the ingredients tested, only corn gluten meal (7.35% compressibility and 1.08 HR) could be considered to have a favourable flowability in the current study when interpreting the compressibility and HR results.

Table 2. Descriptive statistics for the physical attributes of samples (n=52)

Item	Minimum	Maximum	Mean	SD	CV
Angle of repose (°)	21.96	42.34	27.79	4.04	14.54
Compressibility (%)	7.35	57.83	28.40	9.99	35.17
Bulk density (kg m^{-3})	195.65	661.76	450.42	105.29	23.38
Tapped density (kg m^{-3})	354.33	882.35	627.71	110.73	17.64
Hausner ratio	1.08	2.37	1.43	0.23	16.27
Mean bulk density (kg m^{-3})	286.92	704.83	539.06	102.21	18.96

SD – standard deviation; CV – coefficient of variation = [(SD/mean) × 100].

Table 3. Classification of ingredients based on their flow properties using the angle of repose, Hausner ratio, or compressibility

Ingredients	Angle of repose	Hausner ratio	Compressibility
	Easy flow		
Flow Property Class[1]	Excellent[2]	Passable[3]	Fair[2]
Safflower meal	21.96	1.40	28.57
Soybean hulls	22.07	1.36	26.47
Corn gluten meal	24.18	1.08	7.35
Sunflower meal	24.68	1.26	20.38
Soybean meal	25.06	1.28	20.93
Mean	23.59	1.27	20.74
	Moderate flow		
Flow Property Class[1]	Excellent[2]	Very poor[3]	Poor[2]
Pumpkin seed meal	26.67	1.57	36.13
Wheat DDGS	26.86	1.28	21.98
Sunflower hulls	27.32	1.53	34.31
Wheat bran	27.35	1.43	29.49
Meat and bone meal	27.47	1.71	41.38
Sunflower seed	27.66	1.66	39.78
Corn DDGS	28.19	1.33	24.76
Beet pulp	28.28	1.37	27.21
Corn	28.89	1.40	27.68
Alfalfa	29.76	1.33	24.97
Cocoa hulls	29.92	1.37	27.18
Sunflower meal (extra fat)	29.97	1.78	43.70
Mean	28.19	1.48	31.55
	Cohesive		
Flow Property Class[1]	Good[2]	Very poor[3]	Very poor[2]
Wheat	30.20	1.41	29.15
Barley	30.79	1.72	41.80
Cotton seed meal	30.88	1.82	43.67
Corn (extra fat)	31.79	1.51	33.65
Barley, flaked	32.16	1.94	48.39
Corn bran	32.97	1.39	27.82
Oat	33.20	1.83	45.38
Wheat middlings	34.48	1.46	31.45
Corn gluten feed	38.71	1.32	24.44
Mean	32.80	1.60	36.20

[1]Flow property classification using Hausner ratio and compressibility were done using the mean value for each group; according to [2]Carr (1965), [3]Hausner (1967).

Compressibility (48.4%) and HR (1.94) were found to be highest for barley (flaked), and lowest (7.3% and 1.08, respectively) for corn gluten meal. Barley (flaked) was found to have an *AR* value of 32.16° in the current study, which was consistent with the 34.35° *AR* value revealed by Hamdani *et al.* (2014) for hulled barley. These relatively high *AR*, HR, and compressibility values imply that barley had poor flow properties and hence it was classified among the "cohesive" ingredients in the current study. Oats were also classified among the ingredients with "cohesive" properties since it had relatively high *AR* (33.20) and HR (1.83) values which were also in line with those of Hamdani *et al*. (2014). The average *AR* value of 30.88° for cottonseed meal in the present study agreed with the *AR* value of 35° as reported by Mohsenin (2020). Khazaei and Ghanbari (2010) reported *AR* values of between 28 and 35° for wheat, which were close to the 30.20° reported in the current study. Tumuluru *et al*. (2014) reported that the HR values of ground wheat using hammer-mill screen sizes of 25.4 and 19.05 were 1.37 and 1.52, respectively. It was reported that wheat flour can be characterized as a cohesive powder due to the cohesive characteristics of its particles (Teunou *et al*., 1999). Cottonseed meal and wheat had high HR and compressibility values, and these values correspond to very poor flow properties. Therefore, cottonseed meal and wheat were within the range of the "cohesive" category in the current study. The average *AR* value was found to be highest (38.7) for corn gluten feed. The corresponding flowability category for corn gluten feed, corn bran, corn (full-fat), barley (flaked), and wheat middlings was also defined as "cohesive" in the current study.

The average *AR* value for the corn samples was 28.89° in the current study, which was within the range of (15.7 to 30.2°) as disclosed by Bhadra *et al*. (2017). Jadhav *et al*. (2017) reported 25 to 36° *AR* values for corn samples ground to different particle sizes (1076 to 1996 microns). Higher HR (1.60) and compressibility (36.4%) values were reported for corn with a 10% moisture content and a 0.54 geometric mean diameter by Probst *et al*. (2013) as opposed to 1.40 HR and 27.68% compressibility values found for corn samples ground to pass through a 0.50 mm screen in the current study. The *AR* value for sunflower seeds (intact) with a moisture content range at 4-20% was reported to be between 34 and 41° by Gupta and Das (1997) which was higher than the 27.66° *AR* value in the present report. However, the sunflower seeds used in the present study were milled to cross through a 0.50 mm screen, and those used in the study of Gupta and Das (1997) were whole intact seeds that could have played a role in producing that specific set of results. Importantly, the larger the particle size, the lower the *AR* value; however, the influence of particle size on flowability has been reported to be material-specific (Liu *et al*., 2008). Therefore, the particle size effect assumption concerning flowability may not be true when comparing the whole intact sunflower seeds in the study of Gupta and Das (1997) to the ground ones used in the current study. Powders can become cohesive and this may result in flow problems when particle size falls to below 0.10 mm, which is lower than the particle size achieved by grinding samples passed through a 0.5 mm screen in the current study (Liu *et al*., 2008). Thus, the relationship between different particle sizes and flowability in different ingredients requires further study. Moreover, grinding or milling procedures and storage conditions also affect the flow properties of ingredients, which complicates the interpretation of flowability results across studies (Steckel *et al*., 2006). Corn DDGS produced 28.19° *AR* and 1.33 HR values in the current study, which were within the range (25 to 29° *AR* and 1.23 to 1.39 HR) as reported by Pekel *et al*. (2020). The corresponding flowability category for corn, sunflower seed, corn DDGS, wheat DDGS, sunflower meal (full-fat), sunflower hulls, wheat bran, alfalfa, cocoa hulls, beet pulp, pumpkin seed meal and meat and bone meal was defined as "moderate flow" in the current study.

The *AR* values for soybean meal varied between 23.6 to 28.9° for 9 samples in the current study, which was smaller than those from Wang *et al*. (1995) who reported *AR* values of between 30.3 and 33.2° for soybean meal with 0.833 mm being the normal mean particle diameter. A HR value of 1.08 for corn gluten meal in the present report was found to be similar to that of (1.01) found by Jiang and Rosentrater (2015). The average *AR* value was lowest (21.9°) for safflower meal followed by soy hulls (22.07°). The corresponding flowability category for safflower meal, soybean meal, soy hulls, corn gluten meal and sunflower meal was defined as "easy flow" in the current study.

Oilseed meals (safflower, corn gluten meal, sunflower, soybean and pumpkin seed) had the lowest *AR* values among the tested ingredients, ranging between 22 and 27° (Table 3). Therefore, oilseed meals had the best flowability characteristics in the current study. In addition to Carr's classification, any solid material having *AR* values of between 25 and 35° is regarded as having a favourable flowability in practice (Bhadra *et al*., 2009). The *AR* values for the ingredients used in the present report varied from 22 to 35°, with the exception of corn gluten feed with 39° *AR* values. Therefore, apart from corn gluten feed, the other ingredients would be considered to have a favourable flowability when the *AR* value is taken into consideration. Hausner ratio values greater than 1.25 typically indicate that the substance has inferior flow characteristics, by contrast, values below 1.25 are evidence of satisfactory flowability (Hausner, 1967). The HR value of the ingredients was estimated to lie between 1.08 and 1.94 in the current study. Only corn gluten meal may be considered to have a favourable flowability by using HR as an indirect way of interpreting the flow characteristics since only it had an HR value (1.08) lower than 1.25 in this trial. Therefore, there is a contradiction between *AR* and HR when it comes to interpreting the

Table 4. Correlations (R) between nutrients and physical attributes for ingredients (n=52)

	Angle of repose	Compressibility	Bulk density	Tapped density	Hausner ratio	Mean bulk density
Dry matter	NS[2]	NS	NS	NS	NS	NS
Crude ash	NS	NS	NS	0.28*	NS	NS
Ether extract	0.31*	0.44**	NS	NS	0.41**	NS
Crude protein	–0.42**	–0.38**	0.58***	0.45***	–0.29*	0.54***

Denotes significant correlation at: *p<0.05, **p<0.01, and ***0.001, respectively; NS – not significant.

significance of these values for the evaluation of the flowability of feed ingredients. Thus, it would be of great importance to develop a protocol for the evaluation of the flowability of feed ingredients, with reference to both *AR* and HR.

The ether extract had a positive correlation with *AR* (*r* = 0.31). On the other hand, crude protein displayed a negative correlation with *AR* (*r* = –0.42, Table 4). Similarly, Groesbeck *et al*. (2006) reported that flowability decreased with increased fat content in ground corn samples. The flowability of a powder can be affected by its fat, sugar, protein, and fibre content (Juliano and Barbosa-Cánovas, 2010). Similarly, Perez and Flores (1997) reported that a high fat content can lead to a decrease in flowability. One possible explanation for decreased flowability with high-fat content may be an increase in stickiness between the feed particles. Also, the location of fat molecules in the powder is also an important aspect which affects flowability. This principle is further supported by the fact that powders with high levels of surface fat showed a lower degree of flowability (Vignolles *et al*., 2007). Therefore, the surface composition of feed particles may be an important contributor to the overall flowability of ingredients. On the contrary, Pekel *et al*. (2020) reported that there was no correlation between nutrient levels including the ether extract and *AR* properties of corn DDGS samples. However, a notable correlation was encountered between *AR* and fat and protein content, the *r* and r^2 values were not high enough to be of practical value in this trial. Compressibility was positively correlated (*r* = 0.44) with the ether extract content and negatively correlated (*r* = –0.38) with the crude protein content of the feed ingredients tested in the current study. Full-fat sunflower meal had approximately 2 times more compressibility (43.70%) than regular sunflower meal (20.38%) in the current study. Similarly, full-fat corn was found to have a greater compressibility value than regular corn in the current study (33.65 vs 27.68%). As crude protein levels increased, *BD* (*r* = 0.58), *TD* (*r* = 0.45), and MBD (*r* = 0.54) increased. In general, density increases with increasing protein content in the ingredients, this was confirmed by the current study (Rupp *et al*., 2018), although correlations were moderate (0.45 to 0.58). There were relatively low correlations between *TD* and crude ash (*r* = 0.28) and also between HR and ether extract (*r* = 0.41). The prediction equations which were calculated using significant correlations between the physical and chemical properties are given in Table 5.

Table 6. Correlations (R) between different physical attributes for ingredients (n=52)

	Compressibility	Bulk density	Tapped density	Hausner ratio	Mean bulk density
Angle of repose	0.59***	–0.45***	NS	0.62***	–0.32*
Compressibility	–	–0.67***	NS	0.97***	–0.39**
Bulk density	–	–	0.79***	–0.64***	0.94***
Tapped density	–	–	–	NS	0.95***
Hausner ratio	–	–	–	–	–0.37**

Explanations as in Table 4.

The *AR* values had an inverse correlation with *BD* (*r* = –0.45) and MBD (*r* = –0.32, Table 6). Since BD, TD, and MBD are different ways of determining the density of solids, the higher the *BD* value, the higher the *TD* (*r* = 0.79) and MBD (*r* = 0.94) values. Similarly, the higher the *TD* value, the higher the MBD (*r* = 0.95) value. The HR value was negatively correlated with the *BD* (*r* = –0.64) and MBD (*r* = –0.37) values. Compressibility was found to be negatively associated with *BD* (*r* = −0.67) and MBD (*r* = –0.39). It was found that the compressibility of solid materials was influenced by the density, particle size/shape of the particles, moisture content, and also the cohesiveness of the materials (Yan and Barbosa-Canovas, 1997; Hamdani *et al*., 2014). The HR value was positively correlated with both *AR* (*r* = 0.62) and compressibility (*r* = 0.97) in this trial, this complied closely with results reported for corn DDGS (Pekel *et al*., 2020). Since HR is a function of *TD* and BD, and these parameters may provide indirect information about compressibility, a greater HR value results in a higher degree of compressibility (*r* = 0.97, r^2 = 0.95, Table 7). Similarly, a very high degree of correlation was shown by Bhadra *et al*. (2009) between the *AR* and HR values for DDGS samples. *AR* was positively associated with compressibility (*r* = 0.59) to a significant extent. Therefore, the higher the compressibility of an ingredient, the higher the *AR* value and consequently the

Table 5. Equations obtained from linear relations between physical and chemical variables (n=52)

	R	R^2	Equation	p
Ash-TD	0.28	0.08	*TD* = 6.8284 × Ash + 589.51	<0.05
EE-*AR*	0.31	0.10	*AR* = 0.1681 × EE + 26.919	<0.05
EE-*C*	0.44	0.19	*C* = 0.5912 × EE + 25.322	<0.01
EE-HR	0.41	0.17	HR = 0.0128 × EE + 1.3609	<0.01
CP-*AR*	–0.42	0.17	*AR* = –0.1123 × CP + 30.839	<0.01
CP-*C*	–0.38	0.14	*C* = –0.2503 × CP + 35.183	<0.01
CP-BD	0.58	0.33	*BD* = 4.0468 × CP + 340.71	<0.001
CP-TD	0.45	0.20	*TD* = 3.3222 × CP + 537.64	<0.001
CP-HR	–0.29	0.08	HR = –0.0045 × CP + 1.5493	<0.05
CP-MBD	0.54	0.30	MBD = 3.6845 × CP + 439.18	<0.001

TD – tapped density; EE – Ether extract; *AR* – angle of repose; *C* – compressibility; CP – crude protein; *BD* – bulk density; HR – Hausner ratio; MBD – mean bulk density.

Table 7. Equations generated from a single linear regression between physical variables (n=52)

	R	R^2	Equation	p
AR-C	0.59	0.35	*AR* = 0.2397 × *C* + 20.988	<0.001
AR-BD	–0.45	0.20	*AR* = –0.0172 × *BD* + 35.557	<0.001
AR-HR	0.62	0.39	*AR* = 10.819 × HR + 12.349	<0.001
AR-MBD	–0.32	0.10	*AR* = –0.0125 × MBD + 34.553	<0.05
C-BD	–0.67	0.45	*C* = –0.0635 × *BD* + 57.004	<0.001
C-HR	0.97	0.95	HR = 0.0227 × *C* + 0.7833	<0.001
C-MBD	–0.39	0.15	MBD = –4.0236 × *C* + 653.32	<0.01
TD-BD	0.79	0.62	*TD* = 0.0008 × *BD* + 0.2532	<0.001
HR-BD	–0.64	0.41	HR = –0.0014 × *BD* + 2.0619	<0.001
MBD-BD	0.94	0.89	MBD = 0.0009 × *BD* + 0.1266	<0.001
MBD-TD	0.95	0.90	MBD = 0.8759 × *TD* – 10.739	<0.001
HR-MBD	–0.37	0.14	HR = –0.0009 × MBD + 1.8873	<0.01

Explanations as in Table 5.

lower the flowability (Carr, 1965). Surprisingly, corn gluten feed had the highest *AR* value, but it did not have a relatively high compressibility value, although there was a significant correlation between *AR* and compressibility. The same phenomena applied in the case of wheat middlings and corn bran that had very high *AR* values (34.5 and 32.9°, respectively) but did not have high compressibility (31.4 and 27.8%, respectively) values. A greater surface fat content has been shown to result in a greater cohesiveness in dairy powders (Fitzpatrick *et al*., 2007). Furthermore, the greater the degree of cohesiveness of a powder, the more inferior the flowability. This explains, although only in part, why the highest *AR* value obtained for the corn gluten feed was attributed to the relatively higher fat content (17%) in this study (Pishnamazi *et al*., 2019). However, although wheat middlings and corn bran had very high *AR* values, they did not have a high fat content as that result discussed above for corn gluten feed. Hence, the cohesiveness hypothesis would not apply to these ingredients from a high fat content perspective.

CONCLUSIONS

1. The greater the protein content, the lower the compressibility (r = –0.38) value and the lower the angle of repose (r = –0.42) value of the ingredients.

2. An increase in the ether extract content of the ingredients resulted in a subsequent increase in angle of repose (r = 0.31) and therefore in a decrease in flowability ($p<0.05$). By contrast, the lower the ether extract content, the lower the compressibility (r = 0.44) and Hausner ratio (r = 0.41) values.

3. The feed ingredients varied widely in their flowability. Oilseed meals were classified as “easy flow”, while most grains were in the “cohesive” category, along with most other ingredients including by-products that were classified as having a “moderate flow”.

4. The Hausner ratio, compressibility, ether extract, and protein content may be regarded as favourable indicators for feed flowability.

5. Feed ingredients with low levels of compressibility, Hausner ratio, and ether extract together with a high protein content may be desirable for improved flow characteristics.

Conflict of interest: The authors declare that they have no conflict of interest.

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