# Hydration capacity: A new criterion for feed formulation

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# Hydration capacity: A new criterion for feed formulation

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## ABSTRACT

Twenty-four raw materials, harvested or produced in 2013 and commonly used in animal feed, were used to measure their hydration capacities through both water-holding capacity (WHC, g $H_2O$/g DM after 24 h of water addition) and swelling capacity (SC, mL $H_2O$/g DM during 60 min after water addition, every 5 min during the first 30 min and then every 10 min). The raw materials were provided in the form of whole seeds (F1 class; $n = 8$), flour/mash/hulls (F2 class, $n = 8$) or pellets (F3 class, $n = 9$). Hydration capacities were measured for unprocessed material and also after grinding of whole seeds (1, 3, 5 or 8 mm grid). The raw materials were analysed for fibre content to study the relation with WHC and SC. Moreover, WHC and SC were measured on twenty-eight compound pelleted feeds containing some of the raw materials studied in the present experiment, harvested or produced in the same year (i.e. 2013; Experimental feeds; $n = 8$) or in an earlier year (i.e. <2013; Reference feeds; $n = 20$) to evaluate additivity and predictability of these criteria. WHC and SC at 60 min (T60) varied greatly among the raw materials (2.88 ± 1.74 g $H_2O$/g DM and 2.61 ± 2.37 mL $H_2O$/g DM, respectively; $P < 0.001$) and are weakly correlated ($R^2 = 0.52$; $P < 0.001$). They are thus two complementary measurements interesting in feed formulation. The physical form of the raw materials at the moment of delivery had a significant effect on WHC (0.97, 4.92 and 3.65 g $H_2O$/g DM in the F1, F2 and F3 classes, respectively; $P < 0.001$). Grinding the seeds had a significant effect on WHC and SC values ($P < 0.001$). WHC and SC at T60 were moderately correlated with the fibre content: neutral detergent fibre (aNDF), acid detergent fibre (ADF), acid detergent lignin (ADL), hemicellulose and cellulose content ($R^2 < 0.40$ and $P < 0.01$ the same for every fibre fraction). In the eight Experimental feeds, the correlation between calculated SC and measured SC at T60 was low ($R^2 = 0.38$; $P = 0.104$). Conversely, the correlation between calculated WHC and measured WHC was high ($R^2 = 0.89$ and $R^2 = 0.81$; in the Experimental and the Reference feeds, respectively; $P < 0.001$) and the mean difference between the predicted WHC and the measured WHC was

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*Abbreviations:* ADF, acid detergent fibre; ADL, acid detergent lignin; D50, median particle size; DM, dry matter; aNDF, neutral detergent fibre assayed with a heat stable amylase and expressed inclusive of residual ash; F1, first class of form of presentation (whole seeds); F2, second class of form of presentation (flour/mash/hulls); F3, third class of form of presentation (pellets); SEM, standard error of the mean; SC, swelling capacity; $SC_5$, the volume reached at T5 (% of $SC_{60}$); $SC_{60}$, the volume observed at T60; T, volume of the sample measured before the water addition (T0) then every 5 min for 30 min and then every 10 min until 60 min (T60 end of the test); WHC, water-holding capacity.

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moderate (9.7% and 10.6%, respectively for Experimental and Reference feeds), but could reach high values (>15%), especially when measured WHC was high. In conclusion, hydration capacity could be considered as additive, however, the theoretical values of pelleted compound feeds should be supported by real measurements.

## 1. Introduction

Formulation of animal feeds is generally based on linear programming to meet the nutritional needs of the animals considering the availability, the price and the nutrient content of the raw materials. It considers some underlying assumptions such as additivity, i.e. the nutritional value of a compound feed is the sum of the nutrient contributions of each ingredient (Pomar et al., 2009).

Studies have shown the interest of the hydration capacity of feeds in animal feeding (Giger-Reverdin, 2000; Serena and Bach Knudsen, 2007; Jiménez-Moreno et al., 2011; Arroyo et al., 2012). Hydration capacity of feeds seems to influence the transit time, organ development (such as birds' crops), feed intake and the feeling of satiety. Although this parameter is sometimes mentioned to explain some results, it is rarely used in feed formulation as a predictive parameter. Gous (2014) noted that water-holding capacity could be a good tool to improve food characterisation models. This would require the availability of databases providing this parameter for the more common raw materials used in animal nutrition. Giger-Reverdin (2000) achieved a first screening for feedstuffs for ruminants, but raw materials used in monogastric animal nutrition are quite different. Furthermore, animals, especially monogastrics, are commonly fed with compound pelleted diets for nutritional and economic reasons (Abdollahi et al., 2013). The grinding and pelleting processes modify physico-chemical properties of the raw material and could alter accessibility of nutrients and feed intake behaviour of the animals. Therefore, the potential use of a new criterion in animal feed formulation needs to study the influence of the grinding and pelleting process and determine whether it complies with the principles of additivity and predictability.

The present study aims to measure hydration capacities, i.e. water-holding capacity (WHC) and swelling capacity (SC), for a wide range of raw materials used in compound feedstuffs for monogastric animals. These two parameters have been shown to be linked to fibre content (Bach Knudsen, 2001). Therefore, the relation between hydration capacities and fibre content was also studied. Finally, the end purpose was to evaluate whether these two parameters satisfy the principles of (i) additivity, i.e. if the hydration capacity of a feedstuff is the weighted sum of the hydration capacity of its ingredients, and (ii) predictability, i.e. if the hydration capacity of a raw material is stable enough from year to year so that hydration capacity of raw material measured here allow to predict the hydration capacity of a compound feedstuff containing raw materials coming from different delivery batches, year of harvest or production.

## 2. Materials and methods

### 2.1. Raw materials

Twenty-four raw materials were studied: oats, wheat, faba bean, corn, barley, pea, sorghum, triticale, carob, soybean hull, sunflower hull, oat bran, wheat bran, dehydrated alfalfa, wheat straw, sugar beet pulp, citrus pulp, apple pomace, sunflower meal, corn distillers' dried grains, rapeseed meal, oat hull, soybean meal and, pine lignocellulosic insoluble fibre (Arbocel R®, J. Rettenmaier and Sohne Company, Rosenberg, Germany). These raw materials were produced or harvested in 2013. At the time of delivery, they were in form of whole seeds (first physical form; F1 class: oat, wheat, faba bean, corn, barley, pea, sorghum, triticale), flour/mash/hulls (F2 class: Arbocel R®, carob, soybean hull, sunflower hull, oat bran, wheat bran, sunflower meal) or pellets (F3 class: corn distillers' dried grains, dehydrated alfalfa, wheat straw, sugar beet pulp, citrus pulp, apple pomace, rapeseed meal, oat hull, soybean meal). Whole seeds (F1 class) were studied both in unprocessed form and after grinding (1, 3, 5 or 8 mm sieve size).

### 2.2. Compound feeds

Additivity of hydration capacities was studied in 8 compound pelleted feeds (referred to as Experimental feeds) made from common ingredients used in animal diets (Table 3; feed no. 1) supplemented with increasing amounts of sugar beet pulp (5, 10, 15 or 20%), or 10% of soybean hull, citrus pulp or oat bran (Table 3; feeds no. 2–8). The ingredients used in the Experimental feeds came from the same delivery batches as the raw materials studied in the present experiment (i.e. 2013). They were ground using a 5 mm sieve before the mixing and pelleting processes. No steam was added during the pelleting process and the temperature at the end of the pelleting process was around 75 °C.

Predictability of hydration capacities was studied using 20 other compound pelleted feeds from previous studies in our laboratory (referred to as Reference feeds) and stored at 4 °C. Reference feeds contained the same raw materials as those cited above in varying concentrations (Table 4; feeds no. 9–28). However, in Reference feeds, the raw materials were harvested or produced in an earlier year (i.e. <2013) than those used to test hydration capacity and to produce Experimental feeds. The

**Table 1**
Chemical composition (g/kg DM) and physical form of the raw materials.

| Item | Physical form[a] | DM (g/kg) | aNDF | ADF | ADL | Hemicellulose | Cellulose |
|---|---|---|---|---|---|---|---|
| Oats | F1 | 88.26 | 20.57 | 7.82 | 2.86 | 12.75 | 4.96 |
| Wheat | F1 | 88.00 | 30.70 | 2.82 | 1.08 | 27.87 | 1.74 |
| Faba bean | F1 | 86.12 | 17.69 | 5.21 | 1.51 | 12.48 | 3.71 |
| Corn | F1 | 88.67 | 9.60 | 2.46 | 0.84 | 7.14 | 1.62 |
| Barley | F1 | 88.91 | 10.72 | 2.59 | 0.60 | 8.13 | 1.99 |
| Pea | F1 | 89.17 | 15.81 | 5.27 | 0.15 | 10.54 | 5.12 |
| Sorghum | F1 | 86.18 | 10.66 | 2.57 | 0.60 | 8.09 | 1.98 |
| Triticale | F1 | 88.43 | 27.34 | 3.23 | 1.54 | 24.11 | 1.68 |
| Arbocel R® | F2 | 91.33 | 94.09 | 76.94 | 25.93 | 17.15 | 51.01 |
| Carob | F2 | 87.87 | 57.93 | 40.17 | 3.41 | 17.76 | 36.76 |
| Soybean hull | F2 | 89.27 | 89.27 | 19.13 | 8.88 | 1.39 | 10.25 |
| Sunflower hull | F2 | 89.75 | 87.08 | 61.33 | 24.32 | 25.75 | 37.01 |
| Oat bran | F2 | 89.13 | 9.78 | 1.51 | 2.62 | 8.27 | <0.1 |
| Wheat bran | F2 | 88.59 | 37.44 | 11.49 | 3.96 | 25.96 | 7.53 |
| Sunflower meal | F2 | 91.14 | 38.18 | 27.55 | 9.41 | 10.63 | 18.13 |
| Corn distillers' dried grains | F3 | 89.63 | 46.58 | 14.03 | 7.69 | 32.55 | 6.34 |
| Dehydrated alfalfa | F3 | 87.46 | 43.46 | 26.89 | 13.79 | 16.56 | 13.11 |
| Wheat straw | F3 | 88.54 | 64.28 | 38.06 | 6.65 | 26.23 | 31.41 |
| Sugar beet pulp | F3 | 88.48 | 45.11 | 20.94 | 1.92 | 24.17 | 19.02 |
| Citrus pulp | F3 | 89.06 | 19.60 | 14.29 | 6.34 | 5.31 | 7.95 |
| Apple pomace | F3 | 88.18 | 55.81 | 38.78 | 30.54 | 17.03 | 8.25 |
| Rapeseed meal | F3 | 88.16 | 87.08 | 61.33 | 24.32 | 25.75 | 37.01 |
| Oat hull | F3 | 92.17 | 74.67 | 36.62 | 7.57 | 38.05 | 29.05 |
| Soybean meal | F3 | 88.02 | 12.27 | 5.83 | 2.12 | 6.44 | 3.71 |

[a] Form of presentation of the raw material at delivery. F1: whole seeds; F2: flour, mash or hulls; F3: pellets.

objective was to verify that the hydration capacities of a compound feed could be reliably predicted from tabulated values of hydration capacities of its ingredients regardless of its year of production.

All the twenty-eight feeds were made at the experimental unit PECTOUL (INRA, France).

### 2.3. Determination of chemical characteristics, particle size and hydration property

The raw materials were analysed for dry matter (DM, 24 h at 103 °C; AFNOR, 1982) and fibrous fractions (neutral detergent fibre (aNDF), acid detergent fibre (ADF), acid detergent lignin (ADL), hemicellulose as aNDF-ADF and cellulose as ADF-ADL) according to the sequential method of Van Soest et al. (1991) using an amylolytic pre-treatment with a thermostable amylase and expressed inclusive of residual ash.

Particle size was measured on raw and ground materials using decreasing sieve mesh size on dry material for whole seeds and flour/mash/hulls and wet material for pellets. The wet method allows the pellets to fall apart before measuring the particle size within the pellet (Lebas and Lamboley, 1999;Table 2 ). The particle size was expressed as median particle size (D50, mm) which corresponds to a virtual screen which would retain 50% of the particles.

The hydration capacities were evaluated measuring the water-holding capacity (WHC) and the swelling capacity (SC). Methods to measure WHC and SC were 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). 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 were added to 2 g of raw material in a burette. The volume of the sample was measured before adding the water (T0), then every 5 min for 30 min and then every 10 min until 60 min (T60; 60 min after adding the water; end of the test). Results of SC were presented as a real volume of water adsorbed at T50 (50 min after adding the water) and T60 ($SC_{50}$ and $SC_{60}$, respectively, as mL $H_2O$/g DM), and as a relative volume of water adsorbed at T5 ($SC_5$, volume reached at T5, as % of $SC_{60}$), or as the speed of swelling between 0 and 5 min or between 5 and 10 min (mL/min). WHC and SC were measured in triplicate (Serena and Bach Knudsen, 2007; Frikha et al., 2011) on the unprocessed or ground materials, the 8 Experimental feeds and the 20 Reference feeds, respectively. To test the additivity and predictability of the hydration capacities, WHC and SC of the 8 Experimental feeds and the 20 Reference feeds were also predicted from WHC and SC of their ground (5 mm sieve) ingredients.

### 2.4. Statistical analysis

Data were analysed by analysis of variance using R software ver. 3.0.0 (R Development Core Team, 2008). Data of hydration capacities were firstly analysed including the effects of raw materials. The effect of physical form of the raw materials (F1, F2 and F3) was also determined, as well as the effect of fineness of grinding for whole seeds. When significant, differences were compared using Duncan's test. Differences were treated as significant when $P \leq 0.05$ and as tendencies at $0.10 > P > 0.05$.

**Table 2**
Particle size distribution (% yield per sieve) and D50[a] of unprocessed materials.

| Item | Sieve diameter (mm) | | | | | | | | | D50[1] (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| | 4.000 | 3.000 | 2.000 | 1.000 | 0.500 | 0.375 | 0.100 | 0.050 | Others[2] | |
| Oats | 0.46 | 44.51 | 53.05 | 1.81 | 0.06 | – | – | – | 0.11[a] | 1.91 |
| Wheat | 0.67 | 92.36 | 6.65 | 0.27 | 0.01 | – | – | – | 0.04[a] | 2.47 |
| Faba bean | 99.92 | 0.06 | 0.01 | 0.01 | 0.00 | – | – | – | 0.00[a] | 3.50 |
| Corn | 96.91 | 2.73 | 0.29 | 0.03 | 0.01 | – | – | – | 0.03[a] | 3.48 |
| Barley | 0.09 | 94.93 | 4.52 | 0.44 | 0.01 | – | – | – | 0.01[a] | 2.47 |
| Pea | 92.17 | 6.59 | 1.16 | 0.07 | 0.01 | – | – | – | 0.00[a] | 3.46 |
| Sorghum | 0.00 | 89.21 | 9.43 | 1.34 | 0.02 | – | – | – | 0.00[a] | 2.44 |
| Triticale | 0.05 | 65.94 | 30.12 | 3.68 | 0.09 | – | – | – | 0.12[a] | 2.24 |
| Arbocel R® | – | – | – | 0.35 | 0.13 | 20.11 | 57.03 | 21.02 | 1.54[b] | 0.07 |
| Carob | – | – | – | – | – | – | – | – | – | – |
| Soybean hull | – | – | – | 53.27 | 29.27 | – | 15.37 | – | 1.69[a] | 0.53 |
| Sunflower hull | – | – | – | 11.78 | 53.92 | 17.86 | 16.23 | 0.19 | 0.02[b] | 0.41 |
| Oat bran | – | – | – | 84.43 | 13.32 | – | 2.16 | – | 0.09[a] | 0.70 |
| Wheat bran | – | – | – | 38.85 | 23.77 | – | 11.96 | – | 25.42[a] | 0.44 |
| Sunflower meal | – | – | – | 43.61 | 30.83 | 8.32 | 14.18 | 2.77 | 0.29[b] | 0.47 |
| Corn distillers' dried grains | – | – | – | 56.84 | 3.69 | 1.95 | 0.80 | – | 36.72[b] | 0.56 |
| Dehydrated alfalfa | – | – | – | 36.19 | 13.45 | 7.22 | 5.15 | – | 37.99[b] | 0.36 |
| Wheat straw | – | – | – | 63.26 | 5.72 | 2.63 | 3.21 | – | 25.18[b] | 0.60 |
| Sugar beet pulp | – | – | – | – | – | – | – | – | – | – |
| Citrus pulp | – | – | – | 40.02 | 6.18 | 2.56 | 4.64 | – | 46.60[b] | 0.07 |
| Apple pomace | – | – | – | 67.13 | 5.79 | 1.83 | 2.51 | – | 22.74[b] | 0.63 |
| Rapeseed meal | – | – | – | – | – | – | – | – | – | – |
| Oat hull | – | – | – | 72.30 | 3.28 | 1.78 | 2.93 | – | 19.71[b] | 0.65 |
| Soybean meal | – | – | 19.08 | 33.97 | 33.70 | – | 12.35 | - | 0.80[a] | 0.55 |

[1] D50: median particle size is a hypothetical screen which would retain 50% of the particles.

[2] Corresponds to particles <0.100 mm (letter a) or <0.050 mm (letter b).

**Table 3**
Ingredient composition and dry matter of the eight Experimental feeds.

| No. of feed | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Ingredients (g/kg) | | | | | | | | |
| Corn | 370.0 | 351.5 | 333.0 | 314.5 | 296.0 | 333.0 | 333.0 | 333.0 |
| Sunflower meal | 300.0 | 285.0 | 270.0 | 255.0 | 240.0 | 270.0 | 270.0 | 270.0 |
| Wheat | 150.0 | 142.5 | 135.0 | 127.5 | 120.0 | 135.0 | 135.0 | 135.0 |
| Barley | 150.0 | 142.5 | 135.0 | 127.5 | 120.0 | 135.0 | 135.0 | 135.0 |
| Calcium carbonate | 20.0 | 19.0 | 18.0 | 17.0 | 16.0 | 18.0 | 18.0 | 18.0 |
| Salt | 10.0 | 9.5 | 9.0 | 8.5 | 8.0 | 9.0 | 9.0 | 9.0 |
| Sugar beet pulp | – | 50.0 | 100.0 | 150.0 | 200.0 | – | – | – |
| Soybean hull | – | – | – | – | – | 100.0 | – | – |
| Citrus pulp | – | – | – | – | – | – | 100.0 | – |
| Oat bran | – | – | – | – | – | – | – | 100.0 |
| DM (g/kg) | 88.81 | 90.32 | 90.31 | 90.28 | 90.42 | 90.13 | 90.06 | 90.03 |

Regressions were carried out to study the relationships between hydration capacity (WHC or SC) and fibre content. Flour of carob was not included in the regression analysis because it is highly reactive with water and it distorts the linear analysis.

## 3. Results

### 3.1. Hydration capacities of raw materials

The variability of WHC was considerable between raw materials: from 0.83 g $H_2O$/g DM for wheat or barley to 5.60 g $H_2O$/g DM for carob (Table 5). The form of presentation of raw materials at the time of their delivery had also a large effect on WHC ($P < 0.001$; Table 6). WHC was lowest and least variable in the F1 class (0.97 ± 0.07 g $H_2O$/g DM) and highest and most variable in the F2 class (4.92 ± 0.53 g $H_2O$/g DM), the F3 class was intermediate (3.65 ± 0.25 g $H_2O$/g DM). The raw material had a significant influence on WHC within the 3 classes (Fig. 1). Within the F1 class, sorghum and corn had the lowest WHC (0.54 and 0.60 g $H_2O$/g DM, respectively) while peas had the highest WHC (1.63 g $H_2O$/g DM; $P < 0.001$). Within the F2 class, carob had a WHC 4 times higher than oat bran (10.91 vs. 1.56 g $H_2O$/g DM; $P < 0.001$). Within the F3 class, sugar beet pulp had a very high WHC (5.55 g $H_2O$/g DM) compared to rapeseed meal (1.51 g $H_2O$/g DM; $P < 0.001$).

SC kinetics also differed greatly between the raw materials (Table 5): from 0.3 mL $H_2O$/g DM for corn to 4.5 mL $H_2O$/g DM for oat hull. The form of presentation of raw materials at the time of their delivery had a large effect on SC ($P < 0.001$;

**Table 4**
Nutrient and ingredient composition of the Reference feeds (g/kg DM).

| No. of feed | Reference | Nutrient levels (g/kg DM except DM) | | | | | Ingredient (g/kg) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DM (g/kg) | aNDF | ADF | ADL | Hemicellulose | Cereals | Meal or hull: by-products | Sugar beet pulp | Dehydrated alfalfa | Others[a] |
| 9 | Knudsen et al. (2013) | 88.2 | 21.5 | 33.8 | 6.0 | 12.3 | 10.4 | 38.9 | 10.8 | 22.5 | 17.4 |
| 10 | Knudsen et al. (2013) | 88.2 | 21.3 | 33.5 | 6.0 | 12.3 | 19.4 | 41.2 | 20.8 | 3.0 | 15.6 |
| 11 | Jacquier et al. (2013) | 88.5 | 24.9 | 39.2 | 7.9 | 14.3 | 7.0 | 28.7 | 20.0 | 20.0 | 24.3 |
| 12 | Jacquier et al. (2013) | 88.0 | 23.4 | 39.5 | 1.5 | 16.1 | 15.4 | 51.3 | 2.7 | 11.0 | 19.6 |
| 13 | Gidenne et al. (2011) | 87.5 | 19.5 | 35.9 | 5.4 | 16.4 | 10.1 | 39.0 | 17.5 | 11.8 | 21.6 |
| 14 | Gidenne et al. (2011) | 87.3 | 19.5 | 34.9 | 5.5 | 15.4 | 8.2 | 55.6 | 13.0 | 10.0 | 13.2 |
| 15 | Gidenne et al. (2014) | 88.5 | 19.9 | 35.7 | 4.6 | 15.7 | 23.0 | 45.8 | 10.0 | 19.0 | 2.2 |
| 16 | Gidenne et al. (2014) | 88.8 | 19.2 | 33.9 | 4.3 | 14.6 | 12.0 | 50.8 | 10.0 | 19.0 | 8.2 |
| 17 | Combes et al. (2014) | 91.4 | 20.1 | 33.6 | 6.4 | 13.5 | 29.5 | 23.0 | 12.0 | 33.0 | 2.5 |
| 18 | Kimsé et al. (2012) | 87.5 | 18.7 | 37.4 | 4.7 | 18.7 | 12.5 | 43.2 | 8.0 | 34.0 | 2.3 |
| 19 | Kimsé et al. (2012) | 86.6 | 8.7 | 20.1 | 2.1 | 11.4 | 54.6 | 30.7 | 2.0 | 7.0 | 5.7 |
| 20 | Martignon et al. (2010) | 92.2 | 20.1 | 38.9 | 5.2 | 18.8 | 17.8 | 47.0 | 5.0 | 21.0 | 9.2 |
| 21 | Guemour et al. (2010) | 91.8 | 25.1 | 8.2 | 1.8 | 16.9 | 28.0 | 69.0 | 0 | 0 | 3.0 |
| 22 | Guemour et al. (2010) | 91.9 | 26.9 | 10.1 | 3.3 | 16.8 | 27.1 | 66.9 | 0 | 0 | 6.0 |
| 23 | Guemour et al. (2010) | 92.0 | 27.9 | 10.4 | 3.3 | 17.4 | 26.3 | 64.7 | 0 | 0 | 9.0 |
| 24 | Arroyo et al. (2015) | 87.5 | 13.0 | 5.6 | 1.6 | 7.4 | 70.1 | 24.4 | 0 | 0 | 5.5 |
| 25 | Arroyo et al. (2012) | 87.5 | 14.6 | 4.9 | 1.2 | 9.7 | 66.3 | 29.5 | 0 | 0 | 4.3 |
| 26 | Arroyo et al. (2012) | 87.6 | 14.2 | 5.4 | 1.5 | 8.8 | 69.3 | 26.8 | 0 | 0 | 3.9 |
| 27 | Arroyo et al. (2012) | 87.8 | 18.8 | 7.2 | 1.8 | 11.6 | 32.4 | 59.3 | 0 | 0 | 8.3 |
| 28 | Arroyo et al. (2012) | 86.9 | 18.9 | 7.0 | 1.9 | 11.9 | 38.8 | 53.3 | 0 | 0 | 7.9 |

[a] Including ingredients having a weak hydration capacity (oil, vitamins, minerals etc.).
ADF, acid detergent fibre; ADL, acid detergent lignin; DM, dry matter; aNDF, neutral detergent fibre.

Table 6). SC at T60 was similar in F2 and F3 classes (3.40 and 3.78 mL $H_2O$/g DM respectively, $P > 0.05$) but was higher than in the F1 class (0.59 mL $H_2O$/g DM; $P < 0.001$). The type of raw material had a significant influence on SC within F1, F2 or F3 classes ($P < 0.001$; Fig. 2). The SC was similar at T50 and T60 for all the raw materials, i.e. swelling was complete, except for sugar beet pulp which had a smaller volume at T50 than at T60 (data not shown). Hydration of raw materials started

**Table 5**
Water-holding capacity (WHC) and swelling capacity (SC) of the unprocessed raw materials.

| Item | WHC (g $H_2O$/g DM) | $SC_{60}$[1] (mL $H_2O$/g DM) | $SC_5$[2] (% of $SC_{60}$) | Speed of swelling (mL/min) | |
|---|---|---|---|---|---|
| | | | | Between T0 and T5 | Between T5 and T10 |
| Sorghum | $0.54^{m}$ | $0.6^{ijk}$ | $100^{a}$ | $0.12^{hij}$ | $0.00^{d}$ |
| Corn | $0.60^{m}$ | $0.3^{k}$ | $0^{i}$ | $0.00^{j}$ | $0.00^{d}$ |
| Wheat | $0.83^{l}$ | $0.6^{ijk}$ | $100^{a}$ | $0.11^{hij}$ | $0.00^{d}$ |
| Barley | $0.83^{l}$ | $0.7^{hijk}$ | $100^{a}$ | $0.15^{ghij}$ | $0.00^{d}$ |
| Triticale | $1.02^{k}$ | $1.0^{ghijk}$ | $100^{a}$ | $0.21^{efghij}$ | $0.00^{d}$ |
| Oats | $1.14^{k}$ | $0.5^{jk}$ | $33^{efghi}$ | $0.04^{j}$ | $0.02^{cd}$ |
| Faba bean | $1.16^{k}$ | $0.5^{jk}$ | $20^{ghi}$ | $0.02^{j}$ | $0.04^{bcd}$ |
| Rapeseed meal | $1.51^{j}$ | $2.5^{fg}$ | $47^{cdefg}$ | $0.23^{defghij}$ | $0.08^{bcd}$ |
| Oat bran | $1.56^{j}$ | $2.3^{fg}$ | $92^{a}$ | $0.43^{cdefg}$ | $0.02^{cd}$ |
| Pea | $1.63^{j}$ | $0.6^{ijk}$ | $50^{cdefg}$ | $0.06^{j}$ | $0.00^{d}$ |
| Corn distillers' dried grains | $2.35^{i}$ | $2.1^{fgh}$ | $82^{abc}$ | $0.35^{cdefghi}$ | $0.07^{bcd}$ |
| Soybean meal | $3.14^{h}$ | $2.7^{ef}$ | $75^{abcd}$ | $0.40^{cdefgh}$ | $0.08^{bcd}$ |
| Citrus pulp | $3.35^{g}$ | $1.9^{fghij}$ | $30^{efghi}$ | $0.11^{hij}$ | $0.11^{bcd}$ |
| Oat hull | $3.44^{fg}$ | $4.5^{cd}$ | $82^{abc}$ | $0.74^{b}$ | $0.11^{bcd}$ |
| Dehydrated alfalfa | $3.55^{ef}$ | $3.8^{de}$ | $65^{abcde}$ | $0.50^{bcd}$ | $0.17^{abcd}$ |
| Sunflower meal | $3.63^{e}$ | $2.7^{ef}$ | $100^{a}$ | $0.53^{bc}$ | $0.00^{d}$ |
| Wheat bran | $3.83^{d}$ | $2.4^{fg}$ | $100^{a}$ | $0.49^{bcde}$ | $0.00^{d}$ |
| Sunflower hull | $3.97^{d}$ | $1.9^{fghij}$ | $53^{bcdef}$ | $0.22^{defghij}$ | $0.15^{abcd}$ |
| Soybean hull | $4.75^{c}$ | $7.0^{b}$ | $85^{ab}$ | $1.12^{a}$ | $0.23^{ab}$ |
| Wheat straw | $4.86^{c}$ | $2.0^{fghi}$ | $42^{defgh}$ | $0.17^{fghij}$ | $0.09^{bcd}$ |
| Arbocel R® | $5.14^{b}$ | $5.2^{c}$ | $96^{a}$ | $1.01^{a}$ | $0.00^{d}$ |
| Apple pomace | $5.15^{b}$ | $4.3^{cd}$ | $11^{hi}$ | $0.09^{ij}$ | $0.21^{abc}$ |
| Sugar beet pulp | $5.55^{a}$ | $10.4^{a}$ | $23^{fghi}$ | $0.47^{bcde}$ | $0.30^{a}$ |
| Carob | $5.60^{a}$ | $2.2^{fg}$ | $100^{a}$ | $0.45^{cdef}$ | $0.00^{d}$ |
| SEM | 0.203 | 0.285 | 4.3 | 0.0376 | 0.014 |
| *P* value | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |

[1] $SC_{60}$: the volume observed at T60.
[2] $SC_5$: the volume reached at T5 (% of $SC_{60}$).
[a–m] Values within columns with different superscript letters indicate a significant difference ($P < 0.05$).
DM, dry matter; SC, swelling capacity; SEM, standard error of the mean; WHC, water-holding capacity.

**Table 6**
Water-holding capacity (WHC) and swelling capacity (SC) of the unprocessed raw materials according to their form of presentation[3].

| Item[3] | WHC (g $H_2O$/g DM) | $SC_{60}$[1] (mL $H_2O$/g DM) | $SC_5$[2] (% of $SC_{60}$) | Speed of swelling (mL/min) | |
|---|---|---|---|---|---|
| | | | | Between T0 and T5 | Between T5 and T10 |
| F1 | $0.97^{c}$ | $0.59^{b}$ | $62.5^{b}$ | $0.09^{c}$ | $0.01^{b}$ |
| F2 | $4.92^{a}$ | $3.40^{a}$ | $90.9^{a}$ | $0.60^{a}$ | $0.05^{b}$ |
| F3 | $3.65^{b}$ | $3.78^{a}$ | $50.7^{b}$ | $0.34^{b}$ | $0.14^{a}$ |
| SEM | 0.464 | 0.93 | 4.3 | 0.035 | 0.014 |
| *P* value | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |

[1] $SC_{60}$: the volume observed at T60.

[2] $SC_{5}$: the volume reached at T5 (% of $SC_{60}$).

[3] Form of presentation of the raw material at delivery.

F1: whole seeds; F2: flour, mash or hulls; F3: pellets.

$^{a-c}$ Values within columns with different superscript letters indicate a significant difference ($P < 0.05$).

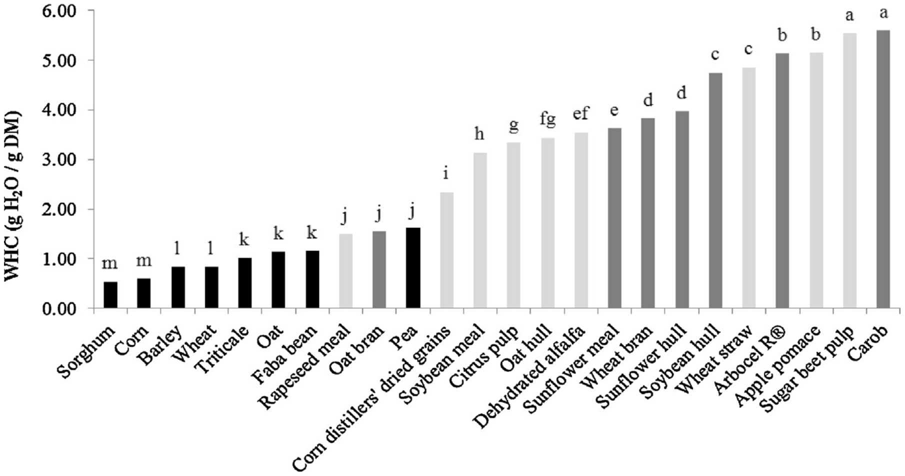

**Fig. 1.** Water-holding capacity (WHC) for each raw material ($n = 24$). The three forms of raw material are distinguished with colours: whole seeds (black), flour/mash/hulls (dark grey), pellets (light grey). $^{a-m}$ Values for which presentation with different superscript letters indicate a significant difference ($P < 0.05$).

very quickly after water addition, as shown by the volume at T5 which was more than 50% of SC at T60 for 16 of the 25 raw materials studied (Table 5). Seven samples had reached complete SC at T5. Only 8 samples had a swelling speed higher than 0.10 mL/min between T5 and T10 (Table 5) indicating a slowing of swelling from T5. In the F3 class, the raw material swelled more slowly, as at T5 none of the samples reached 100% of the SC observed at T60 (data not shown).

The swelling kinetics can be different for raw materials having a similar SC at T60. For example, sunflower hull and citrus pulp had a similar SC at T60 (1.9 mL/g DM) but the volume at T5 (53% vs. 30% of SC at T60) and speed of swelling between T0 and T5 (0.22 vs. 0.11 mL/min) were higher for sunflower hull than for citrus pulp. The relation between WHC and $SC_{60}$ are shown in Fig. 3. The correlation between the two measurements is $R^2 = 0.52$ ($P < 0.001$) but the relation is weaker for higher values of SC and WHC compared lower values.

### 3.2. *Hydration capacity of ground seeds*

The grinding of seeds had a strong influence on WHC and SC values ($P < 0.01$; Table 7). The coarser the grinding of the seeds, the higher was the WHC, as in all samples, the WHC was higher for raw material ground at 8 than at 1 mm. The raw material had a significant effect on SC at T60 in ground samples ($P < 0.001$; Table 8). The sieve mesh size also had a significant effect on SC at T60 for all the samples ($P < 0.05$) except barley and triticale ($P > 0.05$; Table 8).

SC at T60 was maximal for 5 and 8 mm ground samples, i.e. for the coarsest grinding, except for sorghum and wheat for which the highest SC at T60 was observed for the 1 mm and 3 mm mesh sieves, respectively. Overall, SC at T60 tended to decrease when sieve mesh size decreased.

### 3.3. *Hydration capacities of compound feeds*

WHC and SC of the 8 Experimental feeds are shown in Table 9. The relation between calculated and measured values in Experimental and Reference feeds and the distribution of residues are shown in Fig. 4 (WHC in Experimental feed: Fig. 4A1 and A2; WHC in Reference feed: Fig. 4B1 and B2; SC in Experimental feed: Fig. 4C1 and C2).

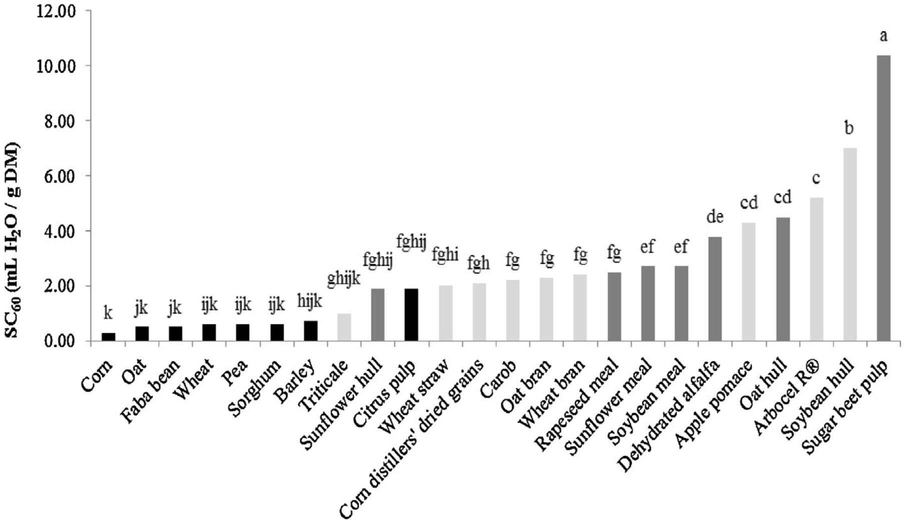

**Fig. 2.** Swelling capacity (SC) for each raw material ($n = 24$). The three forms of raw material are distinguished with colours: whole seeds (black), flour/mash/hulls (dark grey), pellets (light grey). $^{a-k}$ Values for which presentation with different superscript letters indicate a significant difference ($P < 0.05$).

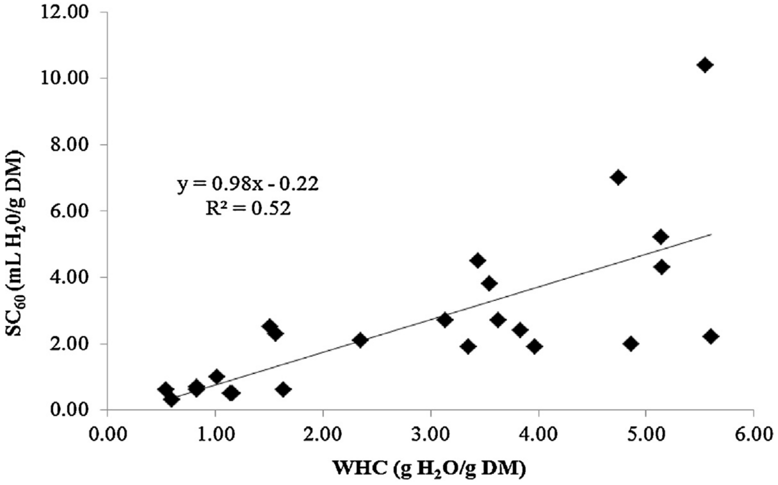

**Fig. 3.** Relation between water holding capacity (WHC) and swelling capacity (SC) for raw materials.

**Table 7**

Effect of sieve size (mm) on water-holding capacity (WHC, g $H_2O$/g DM) of seeds.

| Item | Unprocessed material | Ground material sieve diameter (mm) | | | | SEM | *P* value |
|---|---|---|---|---|---|---|---|
| | | 1 | 3 | 5 | 8 | | |
| Oats | $1.14^{d,B}$ | $1.09^{d,C}$ | $1.51^{c,A}$ | $1.90^{b,A}$ | $2.41^{a,A}$ | 0.133 | <0.001 |
| Wheat | $0.83^{c,D}$ | $0.69^{d,F}$ | $0.79^{cd,E}$ | $1.23^{b,C}$ | $1.42^{a,DE}$ | 0.077 | <0.001 |
| Faba bean | $1.16^{cd,B}$ | $1.09^{d,C}$ | $1.31^{b,BC}$ | $1.27^{bc,C}$ | $1.74^{a,C}$ | 0.062 | <0.001 |
| Corn | $0.60^{d,E}$ | $1.19^{c,B}$ | $1.23^{b,C}$ | $1.30^{a,C}$ | $1.29^{a,E}$ | 0.071 | <0.001 |
| Barley | $0.83^{e,D}$ | $0.99^{d,D}$ | $1.33^{c,B}$ | $1.52^{b,B}$ | $1.71^{a,C}$ | 0.089 | <0.001 |
| Pea | $1.63^{a,A}$ | $1.31^{c,A}$ | $1.48^{bc,A}$ | $1.54^{bc,B}$ | $2.00^{a,B}$ | 0.068 | 0.002 |
| Sorghum | $0.54^{c,E}$ | $1.33^{ab,A}$ | $1.35^{a,B}$ | $1.29^{ab,C}$ | $1.25^{b,E}$ | 0.083 | <0.001 |
| Triticale | $1.02^{c,C}$ | $0.81^{d,E}$ | $1.05^{c,D}$ | $1.35^{b,C}$ | $1.53^{a,CD}$ | 0.072 | <0.001 |
| SEM | 0.069 | 0.045 | 0.047 | 0.046 | 0.079 | | |
| *P* value | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | | |

$^{a-d}$ Values within rows with different superscript letters indicate a significant difference ($P < 0.05$).

$^{A-E}$ Values within columns with different superscript letters indicate a significant difference ($P < 0.05$).

DM, dry matter; SEM, standard error of the mean; WHC, water-holding capacity.

**Table 8**
Effect of sieve mesh size on SC at T60 (mL $H_2O$/g DM) of seeds.

| Item | Unprocessed material | Ground material sieve mesh (mm) | | | | SEM | *P* |
|---|---|---|---|---|---|---|---|
| | | 1 | 3 | 5 | 8 | | |
| Oats | $0.47^{b,BC}$ | $0.00^{b,D}$ | $0.47^{b,CD}$ | $1.13^{a,B}$ | $1.32^{a,B}$ | 0.150 | 0.001 |
| Wheat | $0.57^{b,BC}$ | $0.67^{b,BC}$ | $0.86^{a,BC}$ | $0.57^{b,D}$ | $0.67^{b,C}$ | 0.037 | 0.041 |
| Faba bean | $0.48^{c,BC}$ | $0.58^{c,BC}$ | $1.55^{b,A}$ | $1.65^{ab,A}$ | $1.85^{a,A}$ | 0.157 | <0.001 |
| Corn | $0.28^{c,C}$ | $0.29^{b,CD}$ | $0.29^{b,D}$ | $0.57^{a,D}$ | $0.57^{a,C}$ | 0.037 | <0.001 |
| Barley | $0.75^{AB}$ | $1.13^{A}$ | $0.94^{B}$ | $1.04^{B}$ | $1.04^{B}$ | 0.068 | 0.481 |
| Pea | $0.56^{d,BC}$ | $0.85^{c,AB}$ | $1.69^{b,A}$ | $1.70^{a,A}$ | $1.70^{a,A}$ | 0.132 | <0.001 |
| Sorghum | $0.58^{a,BC}$ | $0.29^{d,CD}$ | $0.58^{a,BCD}$ | $0.58^{a,D}$ | $0.58^{a,C}$ | 0.031 | <0.001 |
| Triticale | $1.04^{A}$ | $0.76^{AB}$ | $0.66^{BCD}$ | $0.85^{C}$ | $1.14^{B}$ | 0.072 | 0.196 |
| SEM | 0.053 | 0.080 | 0.105 | 0.092 | 0.100 | | |
| *P* value | 0.006 | <0.001 | <0.001 | <0.001 | <0.001 | | |

$^{a-d}$ Values within rows with different superscript letters indicate a significant difference ($P < 0.05$).
$^{A-D}$ Values within columns with different superscript letters indicate a significant difference ($P < 0.05$).
DM, dry matter; SC, swelling capacity; SEM, standard error of the mean.

**Table 9**
Measured water-holding capacity (WHC) and swelling capacity (SC) of the eight Experimental feeds.

| Item | WHC (g $H_2O$/g DM) | $SC_{60}$[1] (mL $H_2O$/g DM) | $SC_5$[2] (% of $SC_{60}$) | Speed of swelling (mL/min) | |
|---|---|---|---|---|---|
| | | | | Between T0 and T5 | Between T5 and T10 |
| 1 | $1.76^{de}$ | $3.28^{c}$ | $89^{bcd}$ | $0.58^{c}$ | $0.04^{bc}$ |
| 2 | $1.91^{d}$ | $3.32^{c}$ | $92^{bc}$ | $0.61^{c}$ | $0.06^{b}$ |
| 3 | $2.29^{c}$ | $3.78^{b}$ | $88^{cd}$ | $0.66^{b}$ | $0.06^{b}$ |
| 4 | $2.60^{b}$ | $4.15^{a}$ | $87^{cd}$ | $0.72^{a}$ | $0.06^{b}$ |
| 5 | $3.10^{a}$ | $4.33^{a}$ | $83^{d}$ | $0.72^{a}$ | $0.11^{a}$ |
| 6 | $1.80^{d}$ | $2.22^{d}$ | $100^{a}$ | $0.44^{d}$ | $0.00^{c}$ |
| 7 | $1.76^{de}$ | $3.42^{c}$ | $95^{ab}$ | $0.65^{b}$ | $0.04^{bc}$ |
| 8 | $1.53^{e}$ | $3.24^{c}$ | $89^{bcd}$ | $0.57^{c}$ | $0.06^{b}$ |
| SEM | 0.106 | 0.129 | 1.174 | 0.018 | 0.007 |
| *P* value | <0.001 | <0.001 | <0.001 | <0.001 | 0.007 |

[1] $SC_{60}$: the volume observed at T60.
[2] $SC_5$: the volume reached at T5 (% of $SC_{60}$).
$^{a-e}$ Values within columns with different superscript letters indicate a significant difference ($P < 0.05$).
DM, dry matter; SC, swelling capacity; SEM, standard error of the mean; WHC, water-holding capacity.

In Experimental feeds, WHC (from 1.53 to 3.10 g $H_2O$/g DM) and SC at T60 (from 2.22 to 4.33 mL $H_2O$/g DM) increased when the content of sugar beet pulp increased from 0 to 20% (Table 9). In the same way, the higher the WHC and SC of the raw material added at 10% to the feed no. 1 (to give feeds 2–8), the higher the WHC and SC of the resulting feed. As an example, WHC of sugar beet pulp was higher than those of soybean hull and oat bran (5.55, 4.75 and 1.56 g $H_2O$/g DM, respectively; $P < 0.05$) and WHC of compound feed was higher when it contained 10% of sugar beet pulp compared to soybean hull or oat bran (2.29, 1.80 and 1.53 g $H_2O$/g DM, in feeds no. 3, 6 and 8, respectively; $P < 0.05$). The calculated WHC values of the composed feed are proportional to the WHC value of raw material at an inclusion level of 10%.

In Experimental feeds, the correlation between calculated and measured properties (Fig. 4) was high for WHC ($R^2 = 0.89$; $P < 0.001$) but low for SC at T60 ($R^2 = 0.38$; $P = 0.104$). The difference between the predicted and the measured value was 9.7% for WHC and 52.7% for $SC_{60}$. The residue distribution pattern was not homogeneous. Prediction was worse when measured WHC increased: the difference between the predicted and measured values was 2.0% for feed no. 2 (5% of sugar beet pulp) and 19.1% for No. 5 (20% of sugar beet pulp). For the Reference feed, the correlation between calculated and measured WHC was high ($R^2 = 0.81$; $P < 0.001$). The difference between the predicted and measured WHC was 10.6% on average but could reach 19.1% (for feed No. 5). As observed for Experimental feeds, the distribution of residues was not homogenous, and became worse when WHC increased (Fig. 4B2).

### *3.4. Relation between fibre content and hydration capacities*

The chemical characteristics of the raw materials are shown in Table 1. WHC and SC at T60 were correlated with all fibrous fractions ($P < 0.01$), but correlations were weak: aNDF ($R^2 = 0.37$ and 0.09, respectively; Fig. 5A), ADF ($R^2 = 0.40$ and 0.06, respectively), ADL ($R^2 = 0.23$ and 0.005, respectively), hemicellulose ($R^2 = 0.09$ and 0.09, respectively) and cellulose ($R^2 = 0.39$ and 0.09, respectively). Compared to Experimental feed (data not shown), in the Reference feed (Fig. 5B) the correlations between WHC and type of fibre were generally higher (aNDF: $R^2 = 0.77$; ADF: $R^2 = 0.80$; ADL: $R^2 = 0.62$; hemicellulose: $R^2 = 0.50$) except for cellulose ($R^2 = 0.27$).

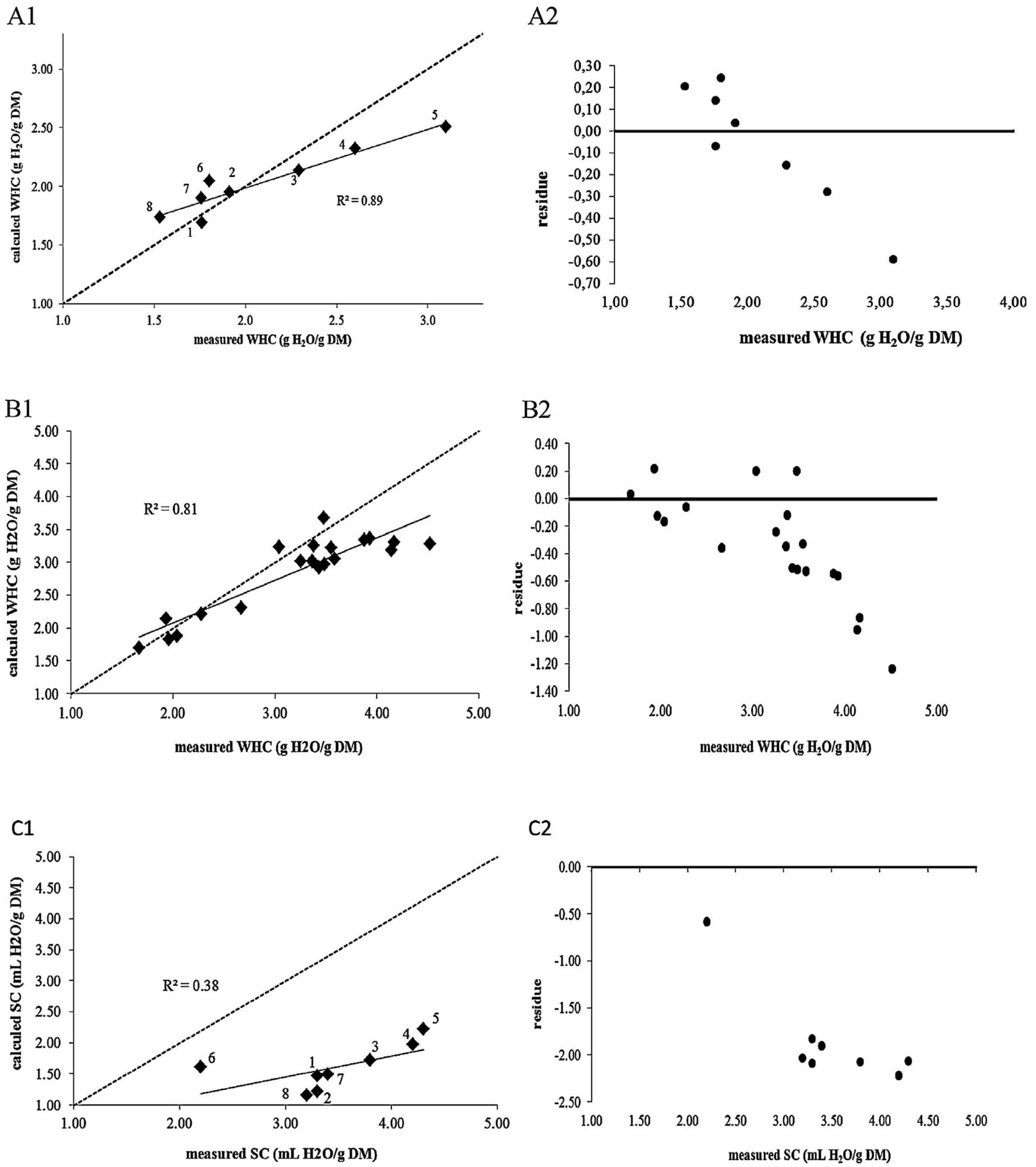

**Fig. 4.** (A1) Relation between measured water-holding capacity (WHC) and calculated WHC ($n = 8$) in Experimental feeds 1–8: see Table 8. (A2) Residue: measured water-holding capacity (WHC) – calculated WHC in Experimental feeds ($n = 8$). (B1) Relation between measured water-holding capacity (WHC) and calculated WHC ($n = 20$) in Reference feeds. (B2) Residue: measured water-holding capacity (WHC) – calculated WHC in Reference feeds ($n = 20$). (C1) Relation between measured swelling capacity (SC) and calculated SC ($n = 8$) in Experimental feeds 1–8: see Table 8. (C2) Residue: measured swelling capacity (SC) – calculated SC in Experimental feeds ($n = 8$).

## 4. Discussion

The present results showed (i) that hydration capacities (WHC and SC) vary greatly among raw materials and are influenced by their physical form at the moment of delivery, their fibre content and grinding, and (ii) that WHC satisfied the principle of additivity but its predictability is moderate.

The data show that WHC and SC varied greatly between the different raw materials. These two parameters are also greatly influenced by the size of particles of the raw material, and their chemical composition, especially the fibre content. WHC was quite low for cereals and high for most of the by-products such as soybean hulls, citrus and sugar beet pulp and sunflower

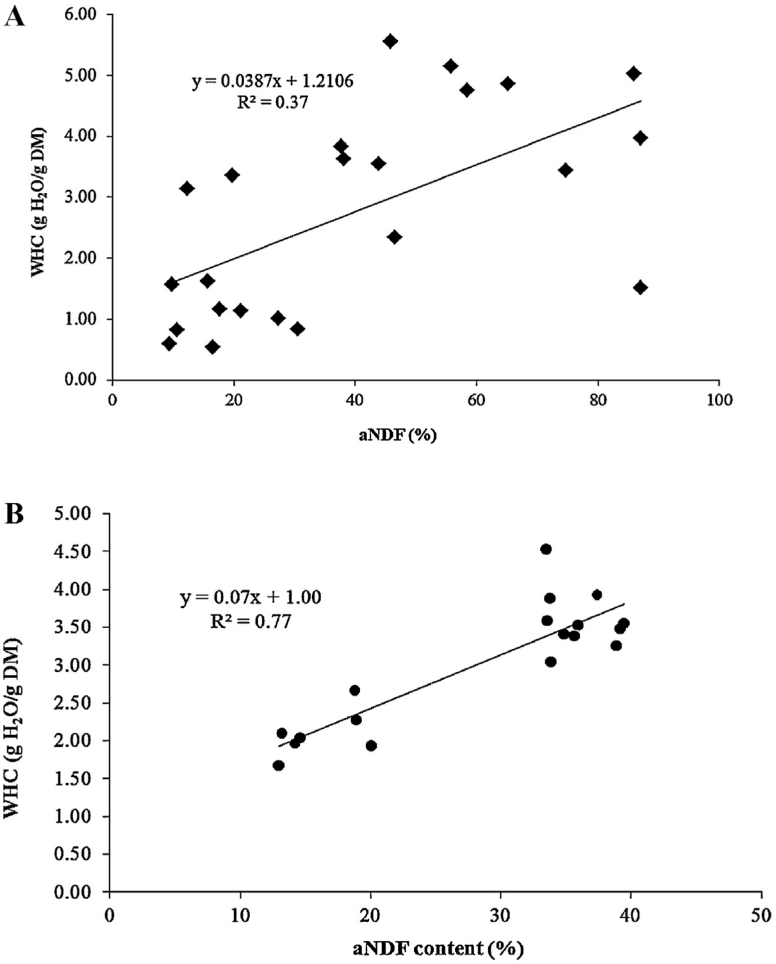

**Fig. 5.** (A) Relation between water-holding capacity (WHC) and neutral detergent fibre (aNDF) content of raw materials ($n = 23$, i.e. all raw materials except carob). (B) Relation between water-holding capacity (WHC) and neutral detergent fibre (aNDF) content of Reference feeds ($n = 20$).

meal, as previously shown (Elleuch et al., 2011; Serena and Bach Knudsen, 2007). Sugar beet pulp has a high hydration capacity, mainly a high swelling capacity. Raghavendra et al. (2006) obtained similar values of WHC (5.00 vs. 5.55 g $H_2O$/g DM) and SC (10.5 vs. 10.4 mL $H_2O$/g DM) as in the present study.

For most of the raw materials, swelling began quickly after wetting, the maximum volume being reached within 5–10 min, as previously shown (Barcia Hernández et al., 1997).

The correlation between WHC and SC values was weak; a high WHC did not necessarily mean a high SC. Consequently, WHC and SC are two complementary measurements; 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). We recommend performing both measurements routinely because they have different meanings. For example, WHC seems more relevant to deal with issues such as litter quality in poultry (Ouhida et al., 2000), while SC seems more suited to solve the issues of crop expansion in waterfowl (Arroyo et al., 2015).

Technological processes have a large influence on hydration capacities of raw materials as demonstrated by the effect of grinding and form of presentation on these parameters. This may be due to an increase in surface area and better accessibility of the surface capillaries to water. Nevertheless, very fine grinding tended to decrease the WHC and SC. Raghavendra et al. (2006) observed a decrease in hydration capacities (water-holding and swelling) 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). Yet very fine grinding reduces the empty interior cellular space which can be filled with water, and the available spaces for free water by collapsing the matrix structure and pores and could also reduce the contact between particles and water and thereby damaging the fibre matrix (Auffret et al., 1994; Raghavendra et al., 2006).

Correlations between fibre and WHC or SC were moderate. Giger-Reverdin (2000) proposed prediction equations of WHC using aNDF ($R^2 = 0.45$) or holocellulose, ADL and starch ($R^2 = 0.76$). Brøkner et al. (2012) showed a correlation of 0.52

for WHC and 0.06 for SC and fibre. Therefore, fibre is insufficient to fully explain hydration properties. Other polysaccharides like starch (Serena and Bach Knudsen, 2007), non-cellulosic polysaccharides like mannose or arabinose, and pectins (Auffret et al., 1994) have also been shown to have an important impact on hydration capacities. Hardness of feedstuffs can also influence hydration capacity (Øvrum Hansen and Storebakken, 2007; Samuelsen et al., 2013).

The correlation between calculated SC and measured SC at T60 was low, and this parameter should thus be considered as weakly additive. Conversely, our data suggest that WHC complies with principle of additivity. Firstly, an increasing proportion of a raw material having a high WHC, such as sugar beet pulp, increased the WHC of the compound feed proportionately. Moreover, the consequences of an addition of 10% of a raw material, namely sugar beet pulp, soybean hull, citrus pulp or oat bran, on the WHC of a compound feed is proportional to the WHC of this ingredient. Finally, the correlation between calculated WHC and measured WHC was high, both for Experimental and Reference feeds. On the other hand predictability of WHC was moderate. Although the mean prediction error was moderate (<11%) for both Experimental and Reference feeds, it could be high (>15%) mainly for certain high WHC values. This can be explained by effects of pelleting or interactions between raw materials within pellets as well as differences in chemical composition among batches (e.g. Reference feeds). Therefore, hydration capacities can be used in feed formulation. However, theoretical values predicted from levels of incorporation of ingredients should be backed up by real values measured on final compound feeds, as measurements on hydration properties are fairly simple, quick and cheap to perform.

The use of hydration capacities in feed formulation can be beneficial to improve animal performance and/or traits (developing of the volume of the crop of geese, Arroyo et al., 2015; improving of feed intake in pigs, Ndou et al., 2013). Quemeneur et al. (2013) concluded that hydration capacity, such as swelling capacity, of feedstuffs is an interesting parameter for diet formulation to be associated with a chemical parameter, like fibre content, and a physical parameter, like hardness, viscosity, or particle size.

## 5. Conclusions

Hydration capacities varied greatly between raw materials and were influenced by technological processes, such as grinding and pelleting, or fibre content. Water-holding capacity and swelling capacity refer to different functional traits and are thus two complementary measurements. Water-holding capacity complies with the principle of additivity and offers interesting prospects in animal feed formulation. However, its predictability is moderate and theoretical values must be supported by real measurements on the final feedstuff. The role of components other than fibre on hydration capacities of a raw material also need to be studied further.

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